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THE CONVERSION OF 16-INCH PROJECTILES TO PRESSURE VESSELS

By

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ABSTRACT

Pressure vessels for use with fresh water and sea water at pressures up to 20,000 psi have been fabricated from modified 16-inch High Capacity Naval Projectiles. Details for modification of projectiles and the fabrication of supporting equipment are presented. Proof testing procedure and data are described and discussed.

CONTENTS

INTRODUCTION

The increasing interest in the study and utilization of the deep ocean as an area of naval operations has brought about a requirement for reproducing various aspects of this environment in the Laboratory. Hydrostatic pressure, an environmental factor second in importance only to corrosion, presents the engineer and researcher with most serious problems. Pressure increases with depth at a rate of about 0.44 psi per foot of depth, with pressures on the order of 16,000 psi possible at the greatest depths.

The design and fabrication of instruments and other devices for deep ocean use requires pressure vessels for testing the design, functioning and watertight integrity of the "package" used to protect such devices from sea water under high hydrostatic pressure. This does not present any real problem when testing small components under moderate pressure. However, the application of such testing to larger components under pressures of several thousands of psi requires the use of facilities which are not normally found in most engineering or research laboratories.

The purpose of this report is to present one solution to the problem of obtaining a medium size (9.5 inch I.D.) pressure vessel at moderate cost. The Mark I (Mk I) pressure vessel design, for use with a noncorrosive media, is capable of being fabricated in any well equipped machine shop. The Mark II (Mk II) design for use with sea water requires the use of heavier equipment and other facilities not normally found in the average machine shop.

The design of these pressure vessels is based on the use of surplus 16-inch, Mk 13, Mod 2 High Capacity, Naval projectiles as the basic vessel body.

The use of projectiles as pressure vessels is not new or unique to this Laboratory. A descriptive article[1] on the use of 16-inch projectiles was published in 1961 by Dr. H. E. Edgerton of Massachusetts Institute of Technology and Mr. L. D. Hoadley of Woods Hole Oceanographic Institution. The publication of this information lead NCEL to investigate the possibility of using these projectiles for its facility.

Subsequent to NCEL's interest in the use of projectiles as pressure vessels, it has been discovered that a number of government and private laboratories have been using various types of projectiles for this purpose.

Definition of Terms

<u>Head</u> - in connection with the 9-inch vessel, refers to the upper (larger) end of the 16-inch projectile when it is in a vertical position with the nose (smaller) end down.

<u>Head Plug</u> - the large plug used to provide a water and pressure tight seal in the head of the vessel. In the case of the Mk I vessel the head plug used is a modified 16-inch projectile base plug. In the Mk II vessel the head plug assembly is of entirely new design and manufacture consisting of a plug and a threaded locking ring.

<u>Base</u> - in connection with the 9-inch vessel, refers to the lower (smaller) end of the 16-inch projectile when it is in a vertical position with the nose end down.

<u>Base Plug</u> - the small plug used to provide a water and pressure tight seal in the base of the vessel. It occupies the position normally occupied by the nose (point detonating) fuse of a projectile.

<u>9" P.V.</u> - For brevity the term 9" P.V. will be used to refer to the 9-inch pressure vessel which actually has an inside diameter of approximately 9.47 inches.

<u>Corrosive Fluid</u> - This term is used to describe any fluid media which would attack the bare, unprotected steel from which the 16-inch projectile and its original component parts were fabricated.

<u>High Pressure Fitting</u> - All high pressure fluid fittings referred to are of the National Bureau of Standards pattern which are described later in the text.

Characteristics of the 16-inch High Capacity Projectile

Of the various types of projectiles which might be used, the 16-inch high capacity type was chosen as offering the largest internal volume. The availability of this type of projectile in government stock was also an important consideration.

The details of the construction of the Mk 13 Mod 2 projectile are contained in reference 2. The basic dimensions of this projectile, as derived therefrom are shown in Figure 1.

Due to the fact that these projectiles are now obsolete, information concerning the exact composition of the steel used in their construction is not readily available. The alloy is generally

described as a special high-capacity projectile Chromium-Nickel-Molybdenum alloy steel with a minimum tensile strength of 105,000 psi and ductility of 18%.

The manufacture and inspection of these projectiles was performed under rigid specifications due to safety requirements and the possible catastrophic consequences of a structural failure or premature burst while in a gun tube. These inspection procedures included X-raying of the finished projectile bodies for structural defects.

Completed vessels fabricated from the projectiles were proof tested at NCEL before use. The procedure and results are described later in the text.

MARK I 9-INCH I.D. PRESSURE VESSEL

The Mk I design is suitable for use with non-corrosive fluid media such as hydraulic oil or fresh water with a rust inhibiting agent added. It can be used with corrosive fluid media by using a rubber bag or some other container in the vessel to isolate the corrosive material from contact with the body of the vessel. This design has the advantage that the machine work required for conversion of the projectiles to pressure vessels can be accomplished in almost any well equipped machine shop. Figure 2 shows the important internal dimensions of the vessel. The appendix contains a list of the vessel drawings available at NCEL.

Figure 3 shows the general assembly of the vessel and Figure 4 shows this semi-portable vessel in use in an outside blast enclosure. It will be noted that of the major components; i.e., vessel body, head plug, base plug and base plug adapter, only the base plug is of entirely new manufacture. All other major components are original parts of the 16-inch projectile with or without modifications.

Vessel Body

In the Mk I vessel the basic projectile body was modified only by (a) removal of the rotating band which is a circumferential, external, copper band located $2\frac{1}{2}$ inches from the large end of the projectile, (when removed, this leaves a recessed groove used to handle the vessel) and (b) the sandblasting of the interior to remove rust and preservative materials.

The Head Plug

The Mk I head plug utilizes the base plug provided with the projectile, but with the following modifications, and as shown in Figure 5:

1. Holes A and A' were bored through the head to receive special high pressure fluid entry fittings shown in Figure 6. These fittings, fabricated from Type 316 stainless steel, provide two fluid entries through the head for use with corrosive fluids.

2. Holes B and B' were bored through the head, counterbored and threaded to receive standard 9/16" O.D. high pressure fittings. These holes provide fluid entries for use with non-corrosive fluids. Details of this female high pressure connection are shown in Figure 5 and the male tubing connection in Figure 7.

3. Holes C and C' are original holes in the plug. These holes are utilized in conjunction with the head plug lifting and turning fixture described later in the text.

4. Hole D, an original opening in the projectile base plug, is utilized as a well for an electrical entry fitting, as described later in the text. It also provides an opening that could be used for a rotating shaft seal, a coaxial cable gland, a viewing port, etc.

5. Hole E was drilled and tapped to receive a ¼-inch O.D. high pressure fitting. This fluid entry is used as a bleed point for bleeding air which may be trapped in the threads between the vessel body and head plug.

6. Hole F was drilled and tapped to receive a ¼-inch O.D. high pressure fitting. This entry is used as a bleed point for bleeding air which may be trapped in the dome shaped cavity in the underside of the head plug.

7. The six G holes in the underside of the head plug were drilled and tapped to receive 3/18-16NC eye bolts for hanging or securing specimens or other equipment under test.

After all machining operations on the head plug were completed the plug was sent to a contractor for application of a dry-film, molybdenum disulphide-type lubricant coating. This coating was found to provide an effective corrosion resisting surface.

The head plug with the stainless steel fluid entry and electrical entry fitting in place is shown in Figure 3. It should be noted that the fittings shown in this illustration are slightly different in design from those shown in Figure 6. The two bleed fittings are shown assembled to the head plug in Figure 5.

The head plug was sealed to the vessel body by use of a metallic backup ring and a rubber "O" ring. These are shown in place in Figure 3. In order to provide optimum sealing surfaces, the underside of the head plug rim was turned on a lathe and a minimum of metal removed to provide a smooth finish for the "O" ring to seal.

Base Plug

The problem of providing a satisfactory seal for the opening in the base of the vessel was somewhat difficult, due to the fact that the original interior finish of the projectile was rough. Since the Mk I design was limited to modifications by machining operations that can be performed using equipment normally found in the average machine shop, no machining of the 1900 pound vessel body was included and other approaches were taken to work around such requirements.

The use of an "O" ring seal between the plug and the vessel wall was not used because it was believed that the rough finish of the interior of the vessel would prevent the "O" ring from providing an efficient seal.

The first vessel fabricated at NCEL utilized the base plug system shown in Figure 3; the details of the component parts of the assembly are shown in Figure 8. This base plug system, which depends on a poured-in-place epoxy seal to make it water and pressure tight, worked satisfactorily at pressures up to 30,000 psi. It is apparent that this is a semi-permanent type of seal and would not be satisfactory if frequent removal or replacement were required. Another disadvantage of this system is that it must be installed through the head opening of the vessel, which is a rather awkward procedure.

The first epoxy seal was used for some months before failure from mechanical damage. The seal broke during a test when an instrument case under hydrostatic test collapsed with a violent implosion at 16,000 psi. The resulting vacuum created by the collapse of a large cavity, and the subsequent shock waves, caused the epoxy material to shatter, and pressure was quickly lost, as the water leaked out around the base plug adapter threads. There was no high velocity water ejected from the vessel, no hazard to the operator and no damage to any vessel component except the epoxy seal. The second epoxy seal is still in service after being subject to over 100 cycles above 10,000 psi. Each of these cycles ended in explosive decompression when test windows were blown out.

An alternate method of sealing the base of the vessel is shown in Figure 9. This method has not been used or tested at NCEL.

Optical Window Head Plug

In order to provide a safe means for the conduct of developmental work on optical windows for the Mk II and other larger non-portable pressure vessels, an optical window head was fabricated for the portable Mk I vessel. This permitted operations to be moved outside of the building to a special blast enclosure during hazardous tests.

The optical window head plug was fabricated by modifying a standard 16-inch projectile base plug. The modifications shown in Figure 10 consisted of providing four 9/16" O.D. high pressure fluid entries, one air bleed passage and a centrally located well which is shown in Figures 11 and 15 and which will be described later in the text. The study on windows is incomplete and results are inconclusive. Tentative findings indicate safe long term operating pressures up to about 10,000 psi, although the short term failure for such a window is 27,000 psi at 70° F.

Electrical Entries

Electrical entries were normally made through the head plug by means of the electrical entry fitting shown in Figure 12. This fitting can accommodate eight standard 1/4 x 28" high pressure single conductor electrical bulkhead fittings.

Mk II 9-INCH I.D. PRESSURE VESSEL

The Mk II design originated from a requirement to modify the Mk I system in such a way that a sea water media could be more readily used in test programs. Simply coating the interior of the Mk I vessel with a corrosion resistant material would not solve the problem, since the seal in Mk I head is located above the threads. (It is doubtful that a corrosion resistant coating could be maintained on the threads). It was decided that a protective coating would be used to protect the interior walls of the vessel, if the seal were made below the threads. This required that the shells be modified to receive new end plugs fabricated from a corrosion-resistant material. These end plugs sealed the openings in such a manner that the threaded, uncoated portions of the vessel were not exposed to sea water. Figure 13 shows the Mk II pressure vessel assembly and Figure 14 shows the important internal dimensions. The appendix lists the drawings of the vessel available at NCEL.

Vessel Body

In general there were three areas of structural modification to the basic projectile body (See Figure 11). The first of these was to adapt the rotating band groove of the shell as a recess for fastening the shell in a holding fixture during use. This modification consisted of cleaning up the groove and removing the existing under cuts.

The second and most extensive modification consisted of opening up the larger end of the projectile from an I.D. of about 9.75 inches to an I.D. of 10.375 inches. This completely removed the old projectile base plug threads.

A new 11" x 2 special acme thread was then machined to receive a new closure locking ring. A 15° taper connected the larger diameter threaded portion with the interior of the vessel and served as the surface against which the head plug seats and the "O" ring makes a pressure tight seal.

The third area of modification was the projectile nose fuze cavity. This cavity was opened up from an I.D. of 3.5 inches to ann I.D. of 4.0 inches, and a new $4\frac{1}{2}$" x 8 thread was cut to receive the lower locking ring. A 5° ramp was then machined to connect the larger I.D. threaded opening to the interior of the vessel and to provide a surface against which the base plug seats and for the "O" ring to seal against.

Following these structural modifications the interior of the vessel was steam cleaned, sand blasted, and electroless plated with .005 inch of nickel.

Subsequent experience with these vessels indicates that in order to get the maximum benefit from the nickel plating, the surface preparation of the internal cavity should include final machining to a smooth finish on the order of 32 to 63 micro inches maximum roughness height.

Head Plug

Both the head plug and the base plug were fabricated from titanium-6Al-4V alloy and with "O" rings for sealing. Both plugs are inserted and seated without any rotation of the plug. They remain stationary while the locking rings are screwed in. The plugs are held in place against internal pressure by means of threaded locking rings fabricated from 4340 steel.

The head plug, see Figure 15, has four fluid entry openings equally spaced on a 5-3/4-inch diameter bolt circle that are machined at both ends to receive standard 9/16" O.D., high pressure fittings. The fluid passages are 1/4-inch I.D.

A centrally located, 2.75" diameter well was provided for use with electrical entry, optical window and other special purpose fittings.

The lower face of the head plug was provided with four 3/8" 16 NC threaded holes on a 5-3/4" bolt circle for purposes of attaching special jigs, specimen hangers, etc. Figure 16 shows the head plug being inserted in a vessel.

Base Plug

The base plugs as shown in Figures 11 and 13 has one fluid entry adapted to receive standard 9/16" O.D., high pressure fittings. The fluid passage is 1/4-inch I.D.

Electrical Entries

The normal method of making electrical entries into the Mk II vessel is by means of the fitting shown in Figure 17. This fitting is inserted into the electrical entry well in the head plug shown in Figure 15. It is provided w th 1/4" x 28 threaded holes to receive a total of eight standard, single-pin, high pressure, bulkhead connectors.

Experience with this electrical entry fitting has shown that it would be desirable to provide a removable dam, as shown in Figure 19, to protect the low pressure side of the fitting from flooding with water in the event that a leak in one of the adjacent fluid fittings should occur. Such leaks, while infrequent, can be a serious problem that can cause considerable delay and inconvenience should they flood the exposed electrical connections with an electrolyte.

Additional single conductor electrical entries can be provided by substituting modified high pressure plugs or nipples (See Figure 19) for the plugs normally used to close the unused fluid entry holes in the head and base plugs. This method must be used when the centrally located electrical entry fitting is replaced by a window or other special fitting.

Special multi-conductor electrical entry fittings can be fabricated to provide in excess of 100 conductors. These fittings would

replace the standard fitting shown in Figure 17. The Mk II electrical entry system can also be used with the Mk I vessel, when the Mk I optical window head plug is used.

Optical Window

In order to provide a means for visually observing devices under test in the pressure vessel, an optical viewing system was developed. This system consists of a metal holder, a truncated cone-shaped optical element and an "O" ring seal. The optical window system is shown in place in Figure 20; the assembled window, in Figure 21; and the component parts, in Figure 22.

SUPPORTING EQUIPMENT AND ACCESSORIES

Mk I Support Frame

The Mk I vessel in its support frame is shown in Figure 23. This support frame is designed so that the vessel may be easily and safely moved by a fork-lift truck. This permits the vessel to be readily moved between a storage area and an operating area. See Figure 24 for construction details of the basic support frame and Figure 25 for details of the fork lift truck adaptor.

Mk II Support Frame

The Mk II support frame was designed to provide more clear access to the base plug and fittings than was provided in the Mk I design. This is also a permanent fixed-type of mounting. Figure 26 shows a Mk II vessel installed in its support frame; Figures 27 and 28 show the details of construction. Phenolic spacers were used between the vessel hangers and the pedestal assembly to reduce heat transfer when the vessels are refrigerated. (See section on refrigeration).

Shields

To protect operating personnel from hazards associated with the possible failure of the vessels and associated high pressure fittings or piping, a missile barrier was provided for use during high pressure operations. While there is no question that a failure of the vessel would involve potential hazard to nearby personnel, especially if it occurred at the maximum operation pressure of 20,000 psi, it should be pointed out that while still serious, the magnitude of the attendant hazard of the failure of a vessel completely filled with water is

less than that involved with the failure of a gas filled vessel at similar pressures.

During the hydrostatic testing of the Mk I vessel, a careful record was kept of the volume of fluid required to change the internal pressure from 4,000 psi to 28,000 psi. Figure 29 is a plot of this data. The graph makes possible determining the amount of water that must be pumped into, or removed from, the vessel for any desired change of the internal pressure. It is apparent from these data that the loss of a small amount of fluid through a rupture, damaged fitting, or seal would cause a rapid drop in pressure in the vessel.

It is the opinion of the NCEL metallurgist consulted, that a failure of the vessel body in normal operation, would not involve fragmentation of the vessel wall and would be unlikely to produce a major projectile hazard. The principal hazard would be from the resultant high velocity, high energy, stream of water and any fittings which might be blown out.

The shields used with the pressure vessels were designed to protect operating personnel from high velocity water and small missiles. One of these shields is shown in place in Figure 30. Fabrication details are given in Figure 31.

A modification of this shield design (addition of a top enclosure) is useful when there is a likelihood that a window in the head plug or some other special fitting might be forcefully ejected through the vessel head. This was determined during the window (view port) development. Figure 32 shows this modified shield in use.

Service Crane

A service platform and hoist with a capacity of 500 pounds was constructed to aid in the insertion and removal of heavy specimen assemblies used in the vessels. Figure 33 shows the hoist in operation and Figures 34 and 35 show construction details.

High Pressure Pumps

NCEL's experience has been that air driven, reciprocating pumps provide the most satisfactory method for supplying the small volumes of fluid at high pressure required for the operation of small pressure vessels. One of the real advantages of this type of pump results from the fact that the pressure output is directly proportional to the air pressure used to operate the pump. The 20,000-psi pump used has a 1 to 200 pumping ratio; i.e., an input air pressure of 100 psi will enable the pump to produce a fluid pressure of 20,000 psi.

This same ratio applies to all but the lowest pressure ranges, where the efficiency of the pump decreases due to the increasing effect of friction in the pump at low air pressures. The advantage of this type of pump is that when the input air is regulated to a certain pressure, it is possible to leave the pump unattended, while the prescribed output pressure is being built up in a vessel. When the pressure in the vessel reaches the preset output pressure (200 times the input pressure) the pump stalls, and thereby, automatically shuts down. It will only resume pumping (again automatically) if the pressure on the output side drops, or the air input pressure increases. It is apparant therefore that a good air pressure supply and regulation system is all that is necessary to regulate fluid pressure with this type of pump. By using two or more of these pumps in parallel, it is possible to gain reliability for long term pumping situations, as occur when pressure must be held against a leak, or a constant bleed, such as might be used to produce circulation in a vessel. If one of the pumps fail, the integral check valves in the pump will prevent loss of pressure through the down pump while the other(s) will continue to maintain the pressure. Figure 36 shows a battery of five of these pumps connected to a manifold system.

Refrigeration

Fulfillment of the purpose of the Mk II pressure vessels to simulate any deep ocean environment required that they have the capability of operating at any temperature from ambient room temperature down to about $-2^{o}C$. The size of the internal cavity precluded the use of internal coils in the vessel. The only remaining solution was to apply the cooling coils to the outside of the vessel. Figure 26 shows the cooling coils used with the Mk II vessels just before the spaces between the adjacent coils and between the coils and the vessel were filled with a heat conducting media. After application of this media, the vessels were wrapped in a foamed plastic insulating material. Figure 37 shows the same vessel after application of the insulation. An automatic temperature control system maintains any preset temperature to $\pm 1^{o}C$.

Experience has indicated that it would be desirable to have an external heat exchanger to pre-cool the water being pumped into the vessel, under circumstances where it is desired to maintain a certain temperature while circulating the fluid media through the vessel during experiments.

Fittings, Valves and Tubing

All fittings, valves and tubing used with the 9-inch vessels are rated for 30,000 psi use and are fabricated from Type 316 stainless steel. These fittings built along the lines of a pipe union

are alternately referred to as a "super-pressure", "ultra-pressure", Bureau of Standards of "Union" type. Figure 7 shows the make-up of a typical connection between high pressure tubing and a female fitting. The tubing used is either 1/4-inch O.D. by .083-inch I.D. or 9/16-inch O.D. by 3/16-inch I.D. seamless type.

The valves used are of the needle valve type and are designed with a captive stem that cannot blow out. The valves, fittings and tubing are available "off-the-shelf" from a number of commercial sources.

The rigidity of 1/4-inch O.D. high pressure tubing and the inherent difficulty of bending, threading and coning type 316 stainless steel make it difficult to fabricate piping systems. This is not a serious problem when making up permanent piping systems, but it does become a cost and time factor when setting up short term, one-use, piping assemblies.

A convenient method for making up "flexible" high pressure connections, where the movement of small volumes of fluid is involved, has been devised. This method utilizes 1/6-inch O.D. by 0.025-inch I.D. seamless type 316 stainless steel tubing. Figure 38 shows the method of making up connections through the use of modified high pressure plugs or nipples. The 1/16-inch O.D. tubing will handle a surprisingly large volume of fluid at high pressures, though the internal friction results in considerable heating of the fluid (at high flow rates) and a drop in pressure. This system is particularly useful in hooking up pressure gages and pressure transducers. A four-or five-foot length of this tubing may also be coiled and used as a gage snubber.

Care should be taken to avoid crushing, kinking or other working of the tubing which could cause strain hardening and brittle failure.

Special Wrenches

Experience with the Mk I pressure vessel has shown that some extrusion of the "O" ring can be expected at pressures in excess of 10,000 psi. This extrusion of the "O" ring may be so severe as to require the use of a spanner wrench and sledge hammer to break the seal. Figure 39 shows one such wrench used with NCEL's Mk I vessel.

In order to be able to screw the head plug in and out without the removal of all the fittings, and to provide a convenient method for lifting the head plug assembly; a special head turning and lifting device shown in Figures 40 and 41 was constructed. Figure 42 shows special wrenches for the tightening and removal of the locking rings on the Mk II vessel.

MK II PRESSURE VESSEL SYSTEM

The Mk II vessel and supporting equipment, accessories and subsystems, some of which were previously described, were integrated into a system consisting of six pressure vessels, a temperature control complex, a sea water pumping system and a sea water storage facility. Drawings (listed in the Appendix) are available showing this integrated system as installed in the NCEL Deep Ocean Simulation Laboratory. The sea water intake, the environmental monitoring sub-system and the 18-inch pressure vessel system referred to in some of the drawings are a part of the overall facility and will be the subject of a separate report describing the whole facility.

PROOF TESTING

Since any internal pressure vessel constituted a potential explosive hazard, proof testing was necessary before the vessel could be placed into service. The proof tests can be of varying complexity and thoroughness, depending on the amount of information desired. The simplest proof test consists of pressurizing the vessel to some overpressure, checking the vessel for cracks, and then releasing the pressure. A more adequate proof test consists of not only pressurizing the vessel, but also of measuring strains on some representative locations, and comparing them to the maximum allowable stresses for the given pressure vessel material. Such a proof test was performed on the Mk I pressure vessel at NCEL.

Procedure

Prior to pressure testing of the vessel, it was instrumented with SR-4 gages (Figure 43); the gages were spaced in fairly regular intervals along the vessels longitudinal axis. Pressure was applied by means of an air-driven pump, that permitted internal pressurizing to 20,000 psi. Pressurizing and reading of the strains required approximately 50 minutes. The pressurization of the vessel from 20,000 psi to 30,000 psi required one additional hour. The pressure was maintained at 30,000 psi for one hour, and then released to zero pressure, at which time, the strains were again recorded. This concluded the proof test.

Discussion

The strains recorded during the proof testing of the vessel were linear and after the reduction of pressure, no permanent set was found to have taken place at the locations where the gages were placed.

Unfortunately the stresses in a thick wall pressure vessel are highest on the interior surface of the vessel. Here the gages are extremely difficult to apply because of limited work space. Also, attendant problems associated with submerged gages at high pressures and the necessary electrical entries render strain gaging the internal surface impractical. The value of the recorded external strains is to verify calculated values. If these two are in agreement, a similar agreement may be assumed for the calculated and experimental stresses on the interior surface of the vessel. Since no gages were placed on the interior of the vessel the calculated stresses were relied upon for information on the magnitude of stresses on the interior of the vessel. The Mk I pressure vessel is a typical thick wall cylinder, and thus, the Lame solution is applicable to the calculations of stresses in such a vessel. Using Lame's solution for the circumferential stresses on the interior of the vessel, in terms of

$$\sigma_{\text{Circ.}} = p\,\frac{(OD^2 + ID^2)}{(OD^2 - ID^2)}$$

and for the circumferential stresses on the exterior of the vessel,

$$\sigma_{\text{Circ.}} = 2p\,\frac{(ID^2)}{(OD^2 - ID^2)}$$

From the above equations the circumferential stresses are calculated to be = σ 1.089p for the interior, and σ 2.089p for the exterior.

The axial stresses in the thick walled vessel are assumed to be uniform across the thickness of the wall, and their magnitude can be calculated by

$$\sigma_{\text{axial}} = p\,\frac{(ID^2)}{(OD^2 - ID^2)}$$

This gives the magnitude of the axial stress as = σ .545p.

Lame's solution assumes that the cylindrical vessel is of such length that the effects of end conditions are negligible on the magnitude of stresses in the middle of the vessel. Since the Mk I pressure vessel has a short D/L ratio, and has quite dissimilar ends, it is to be expected that the agreement between the experimental and analytical stresses will be only fair. When the experimental and calculated stresses for the exterior of the vessel were compared for the gage location in the middle of the vessel's cylindrical portion, they were found to be close, with the calculated stresses generally higher than the experimental ones. At a hydrostatic pressure p of 20,000 psi, the circumferential stress (exterior) was calculated to be 21,700 psi, while the experimental was 19,700 psi; the calculated axial stress was 10,900 psi, while the experimental one was 10,100 psi; and the maximum calculated shear stress was 5,900 psi, while the experimental one was 4,700 psi. This agreement is considered good enough to apply Lame's equation with confidence to the calculation of stresses on the interior of the vessel, directly underneath the exterior gage location whose experimental strains were utilized. (See gage location #3, Table 1). Using Lame's equation, the stresses on the interior of the vessel are calculated to be 41,700 psi for the circumferential stress, 10,900 psi for the axial stress, and 15,400 for the maximum shear stress at 20,000 psi. Since the specifications for the material used in the pressure vessel require that the material have a minimum tensile yield strength of 78,000 psi, ultimate tensile strength of 105,000 psi, and an elongation of 18%, the experimental and calculated stresses appear to be on the safe side when the vessel is operated at 20,000 psi. Even when the pressure inside the vessel is raised to 30,000 psi as was during the proof tests, the calculated and experimental stresses on the cylindrical portion of the vessel midway between the ends of the cylindrical section are below the tensile yield strength of the material.

There is one complication, however, the Mk I pressure vessel is not a perfect cylindrical vessel, but one whose major portion of length is of conical shape. Because of this, the distribution of stresses can be expected to vary from point-to-point on the body of the vessel,and at some points, the stresses may be considerably higher than those existing on the cylindrical portion. To check out this supposition the strains recorded at other points on the vessel were compared to those recorded on the cylindrical portion. The comparison of strains (Table I)shows that the stresses at other points deviate considerably from those on the cylindrical portion, some being considerably larger. The fact that stresses at some other points in the vessel are considerably higher than those on the cylindrical portion, makes it of doubtful value to use the calculated stresses for the interior of cylindrical section of the vessel without qualification, as representing the maximum stresses, and set the operational pressure of the vessel on this basis. Since it is extremely

Table I. Experimental Strain and Stress Data, Mk I Vessel

Location							
Circumferential Strain, micro inches/inch	+ 862	+ 660	+ 556	+ 552	+ 763	+ 395	+ 140
Circumferential Stress, psi	+29,800	+22,200	+19,700	+18,700	+27,500	+13,800	+4,800
Axial Strain,* micro inch/inch	+ 147	+ 45	+ 142	+ 56	+ 234	+ 75	+ 20
Axial Stress, psi	+13,400	+ 8,000	+10,200	+ 7,300	+15,300	+ 6,400	+2,100
Maximum Shear Stress, psi	8,300	7,100	4,800	5,700	6,100	3,700	1,400

*Location of gages shown in Figure 43.
Note: Plus sign denotes tensile values.

difficult to instrument the interior of the vessel, only the measurements taken on the exterior of the vessel exist as an indication of what the interior stresses may be. Using the known relationship between external and internal stresses on the cylindrical portion of the vessel as an approximate ratio for converting the externally measured strains to internal vessel strains at other points, it appears that at between 25,000 and 30,000 psi of internal pressure, the yield point of the material may be reached locally at some point in the vessel. Because of this the operation of the converted 16" Naval gun shells as internal pressure vessels is not recommended at pressures above 20,000 psi, particularly if pressure cycling is to be conducted in the vessel. No known tests have been made to date to determine the fatigue life of such gun shell conversions to pressure vessels.

The experimentally arrived at stresses discussed in the preceding paragraphs pertain almost exclusively to the Mk I vessel version of the converted 16" Naval gun shell. The stresses in the Mk II vessel version, although not experimentally measured so far, are postulated to be lower than those in Mk I vessel. The reason for this is that the end plug was inserted further into the vessel, causing the unpressurized portion of the vessel, where the closure retaining threads are located, to act as a reinforcing end flange. This assists in restraining the expansion of the cylindrical section of the vessel. Thus, Mk II vessel version, is not only easier to operate, but is also a safer vessel.

CONCLUSIONS

Pressure vessels fabricated from Mk 13, Mod 2 16-inch Naval Projectiles are useful up to 20,000 psi internal pressure. With proper precautions to prevent corrosion of the vessel body, they may be used with sea water.

RECOMMENDATIONS

It is recommended that the converted 16" Naval gun shells be not subjected to pressure cycling service at 20,000 psi till experimental data has been generated on which reliable and safe cycling pressure limits can be based.

ACKNOWLEDGEMENTS

Mr. Theodore J. Roster of NCEL designed the Mk I and Mk II pressure vessel conversions.

REFERENCES

1. Edgerton, H. E. and I. D. Hoadley, "Pressure Testing Facility", Underwater Engineering, Vol 2, No. 2, March/April 1961, pp. 29-30.

2. U. S. Navy Bureau of Ordnance, Drawing No. 394294 (Ammunition) 16-inch H. C. Projectile Mk 13, Mod. 2, General Arrangements and Details.

APPENDIX

List of Mk I 9-Inch Pressure Vessel Drawings

61-34- 1F	General Arrangement
61-34- 2F	Piping general assembly
61-34- 3F	Fabricated and modified parts
61-34- 4F	Modification of existing head plug
61-34- 5F	Support frame and pedestal
61-34- 6F	Head plug lifting fixture assembly
61-34- 7F	Head plug lifting fixture fabricated details
61-34- 8F	Shield assembly and miscellaneous details
61-34- 9F	General assembly, vessel
61-34-10F	General assembly, head
61-34-11F	Miscellaneous fabricated details
61-34-12F	Lifting tongs, assembly and details
61-34-13F	Specimen support basket
61-34-14F	Hydraulic assist ram
61-34-15F	Service platform and hoist, assembly and details
61-34-16F	Service platform and hoist, subassembly and details
61-34-17F	Miscellaneous fabricated details

List of Mk II 9-Inch Pressure Vessel Drawings

AMF	60003	Reservoir and high pressure pump installation
	60004	Reservoir support assembly
	60005	High pressure pumps support assembly
	60006	Plot plan, general arrangement and index
	60007	9" pressure vessel piping installation
	60008	Reservoir and high pressure pump installation
	60010	9" pressure vessel cooling system installation
	70000	Hydraulic and air schematic
	80000	9" pressure vessel upper and lower wrenches
	90008	9" pressure vessel Mk II assembly
	90009	9" pressure vessel Mk II, projectile modifications and details
	90010	9" pressure vessel Mk II support assembly
	90011	9" pressure vessel Mk II support details
	90012	9" pressure vessel Mk II shield assembly and details

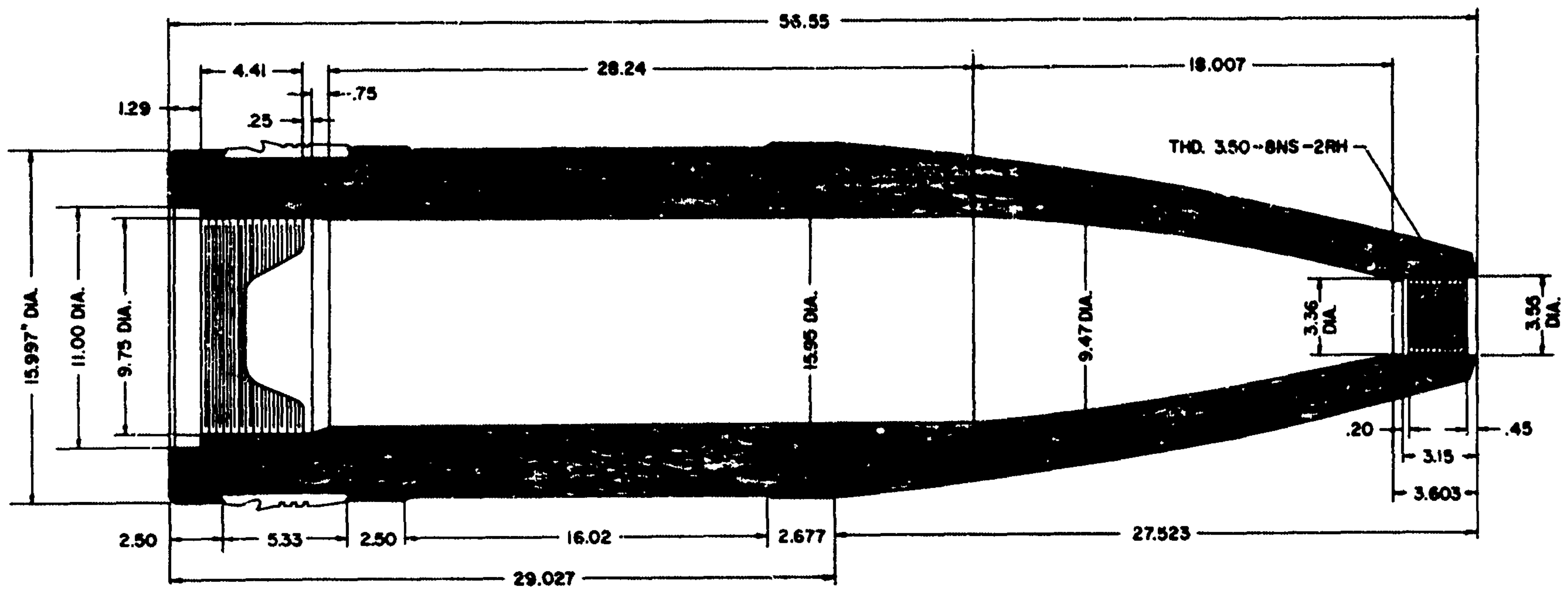


Figure 1. Basic dimension of 16-inch High Capacity projectile Mk-13 Mod. 2

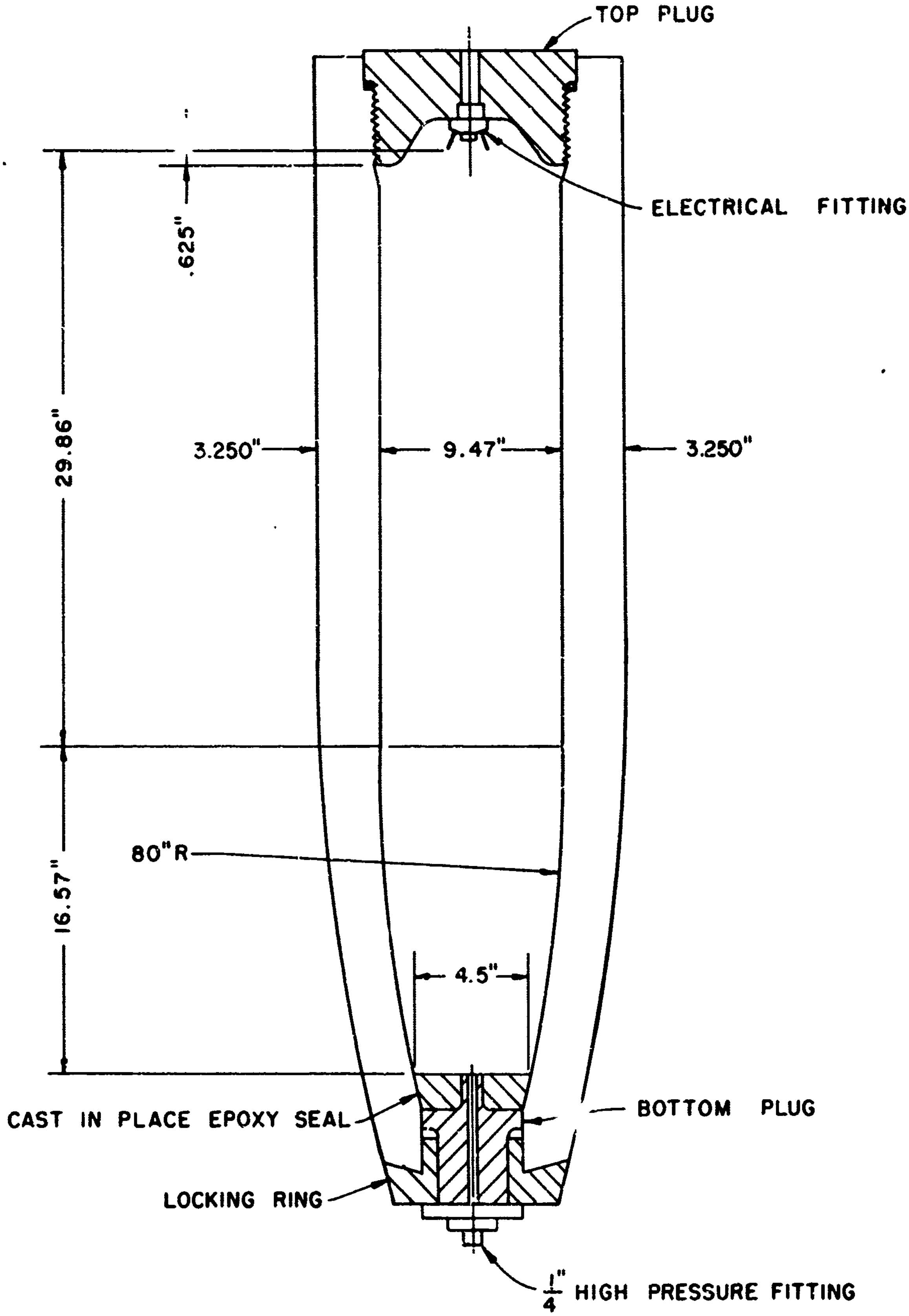


Figure 2. Mk-I pressure vessel internal dimensions.

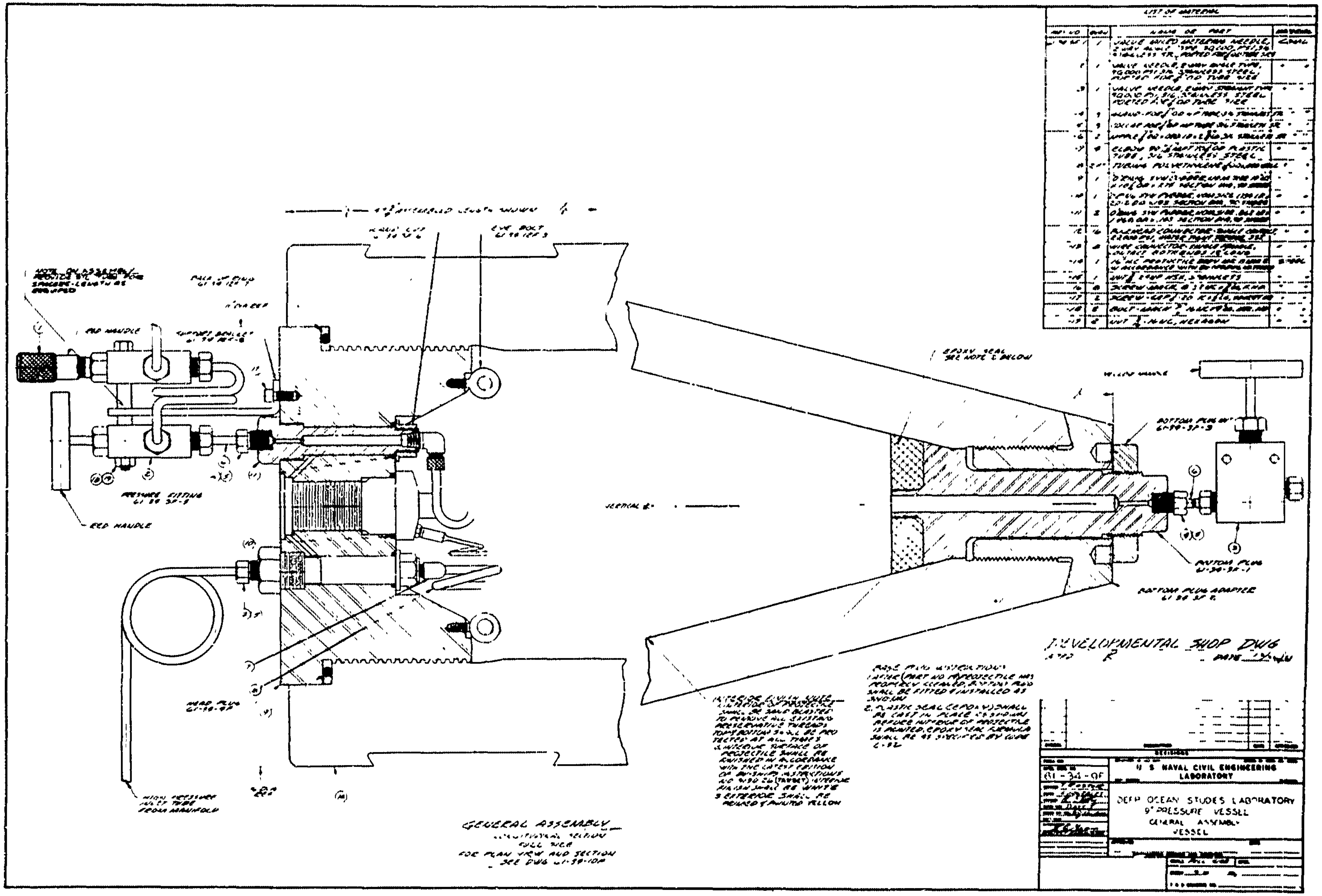


Figure 3. Mk-I pressure vessel general assembly.

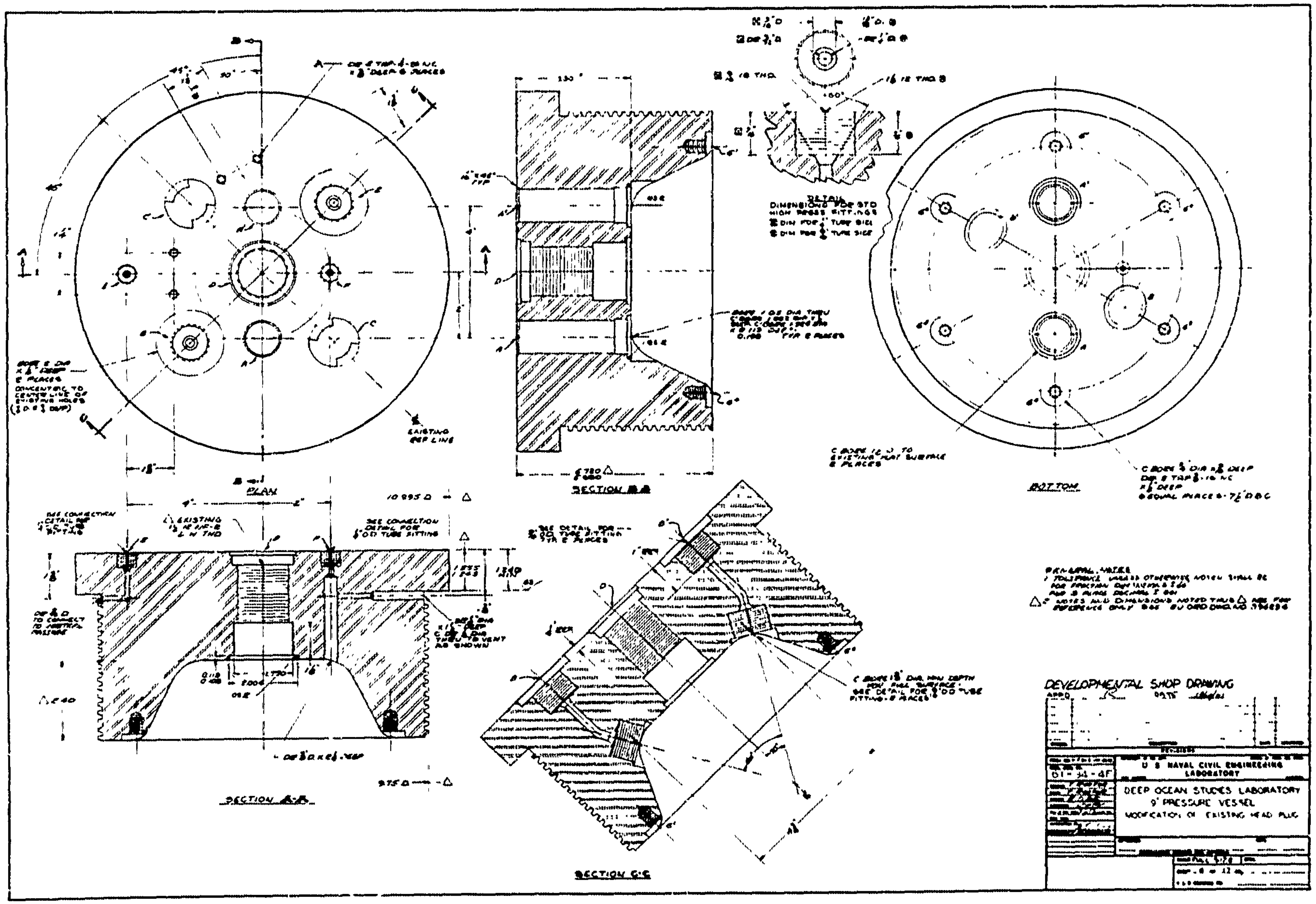
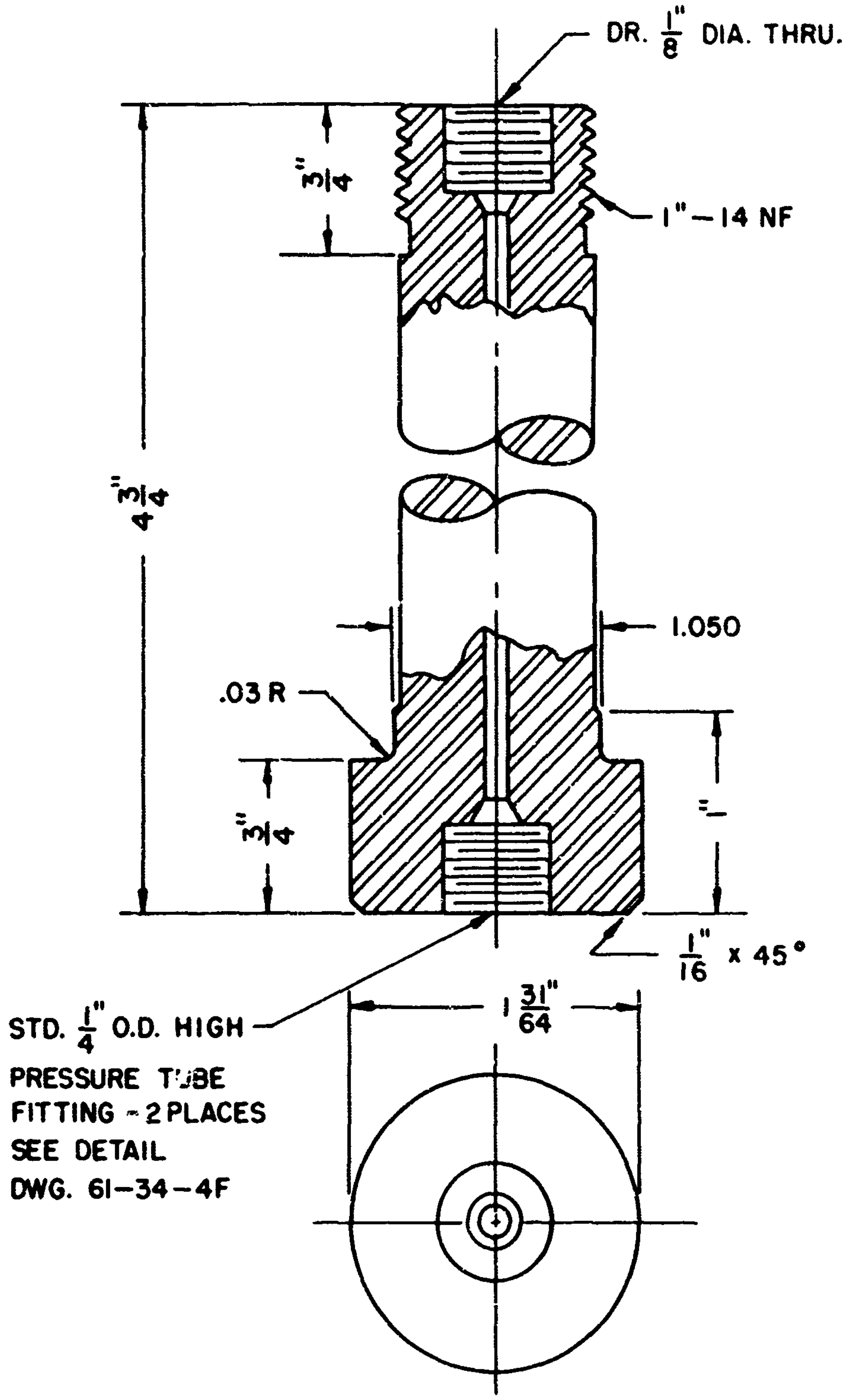


Figure 5. Mk-I pressure vessel head plug details.

Figure 4. Mk-I pressure vessel in outside blast enclosure for proof testing.



HIGH PRESSURE FITTING

TYPE 316 STAINLESS STEEL

2-REQ'D

Figure 6. Fluid entry fitting for use with corrosive fluids in the Mk-I pressure vessel.

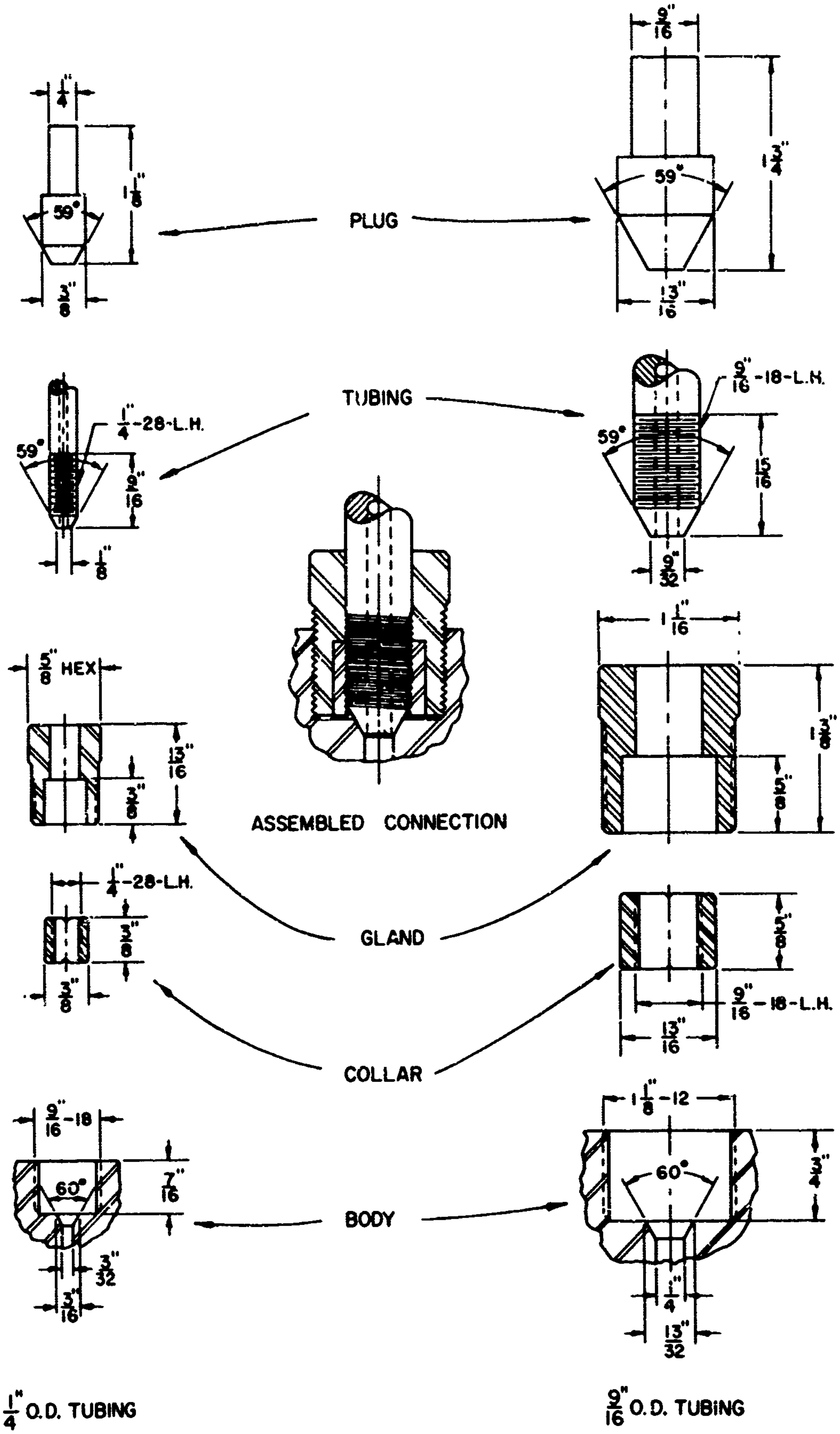


Figure 7. Details of typical high pressure "Union Type" connections.

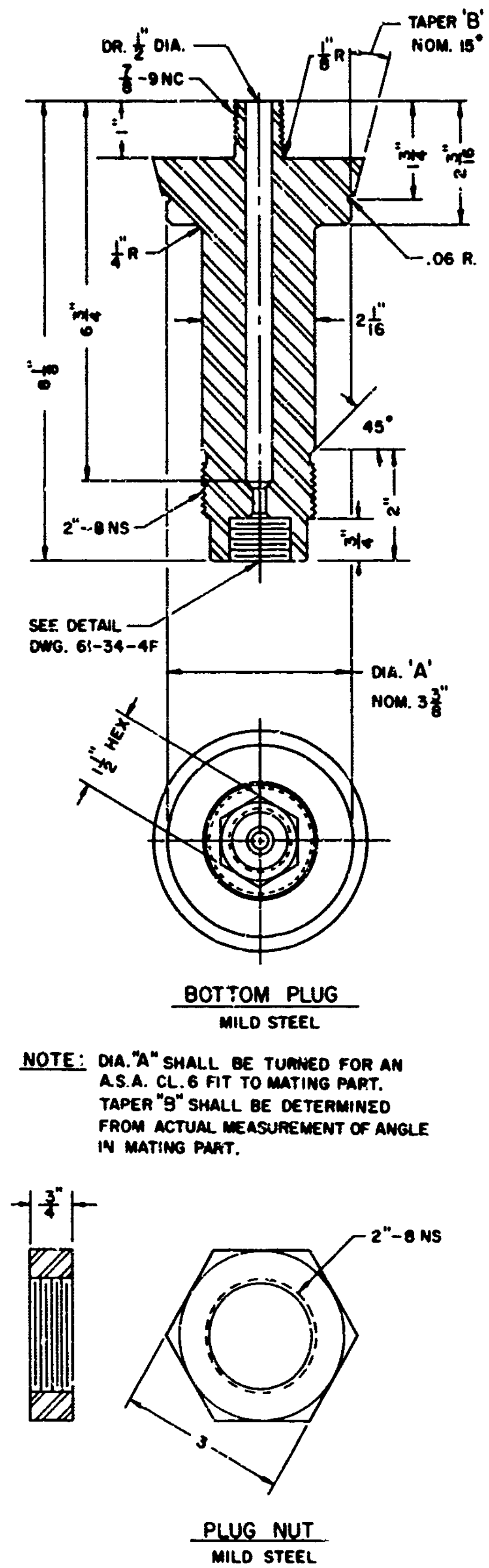


Figure 8. Mk-I mod. 1 base plug sealing system, new parts.

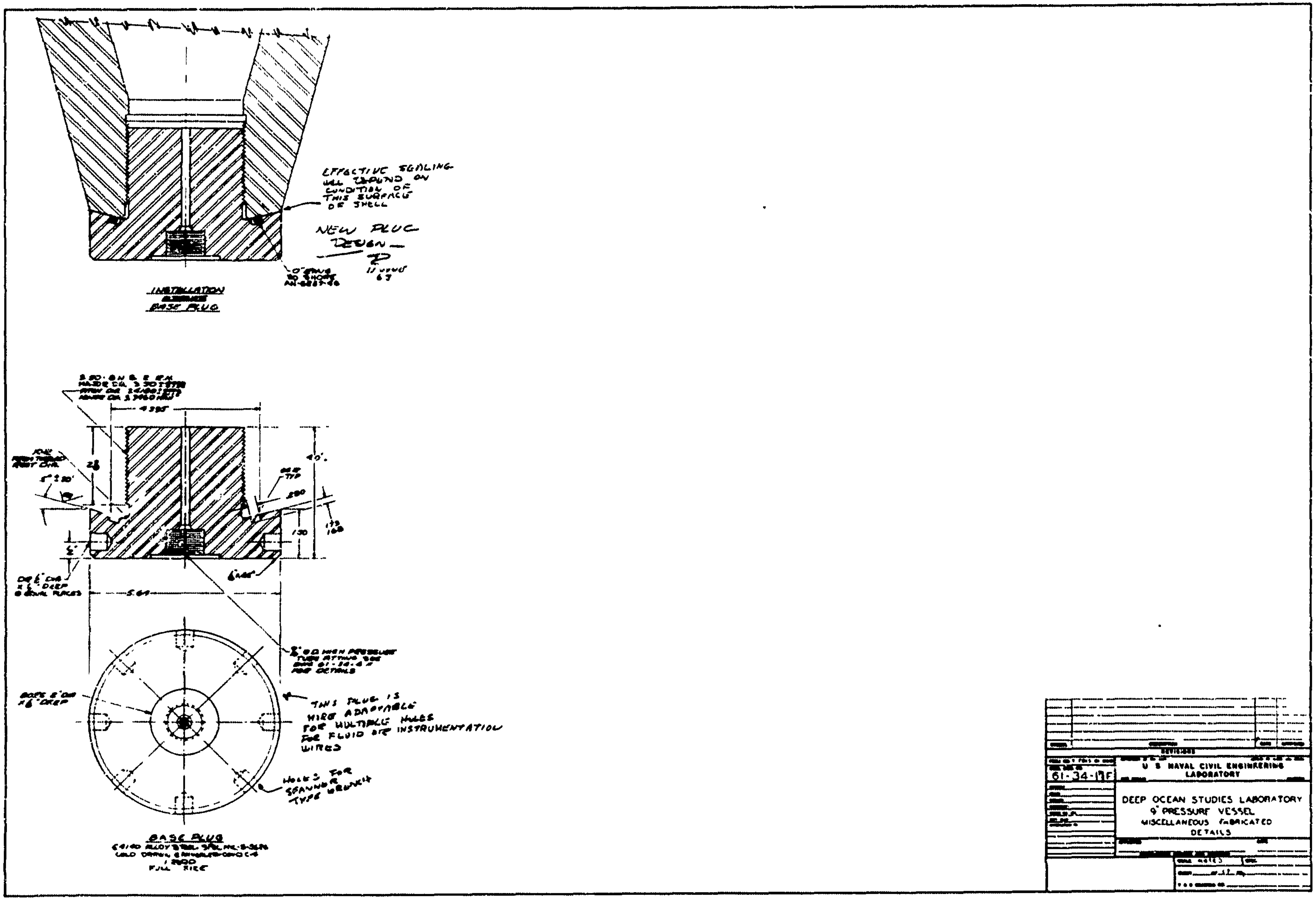


Figure 9. Mk-I mod. 2 base plug sealing system.

Figure 10. Optical window head plug for Mk-I pressure vessel fabricated from original projectile base plug.

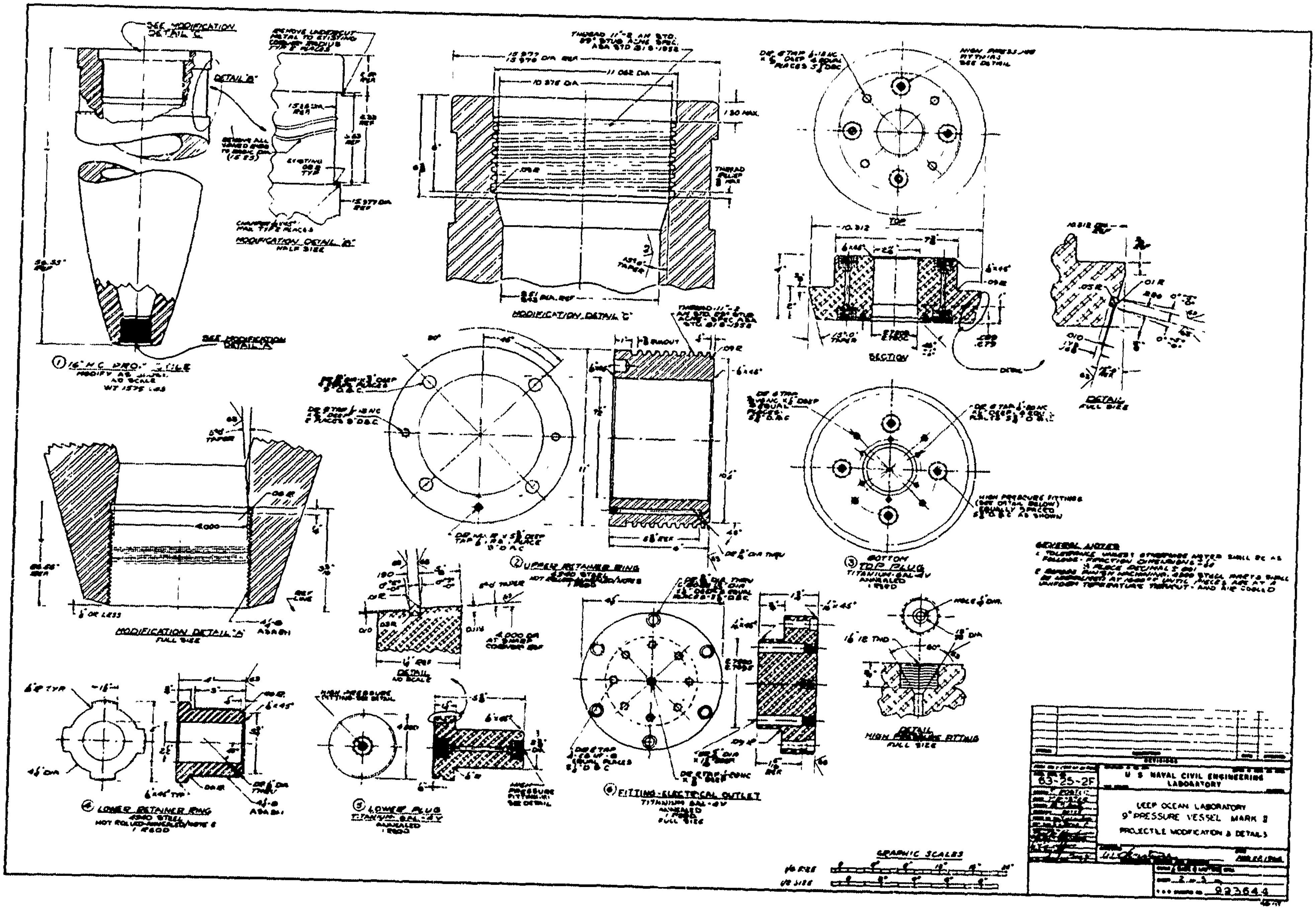


Figure 11. Mk-II pressure vessel details.

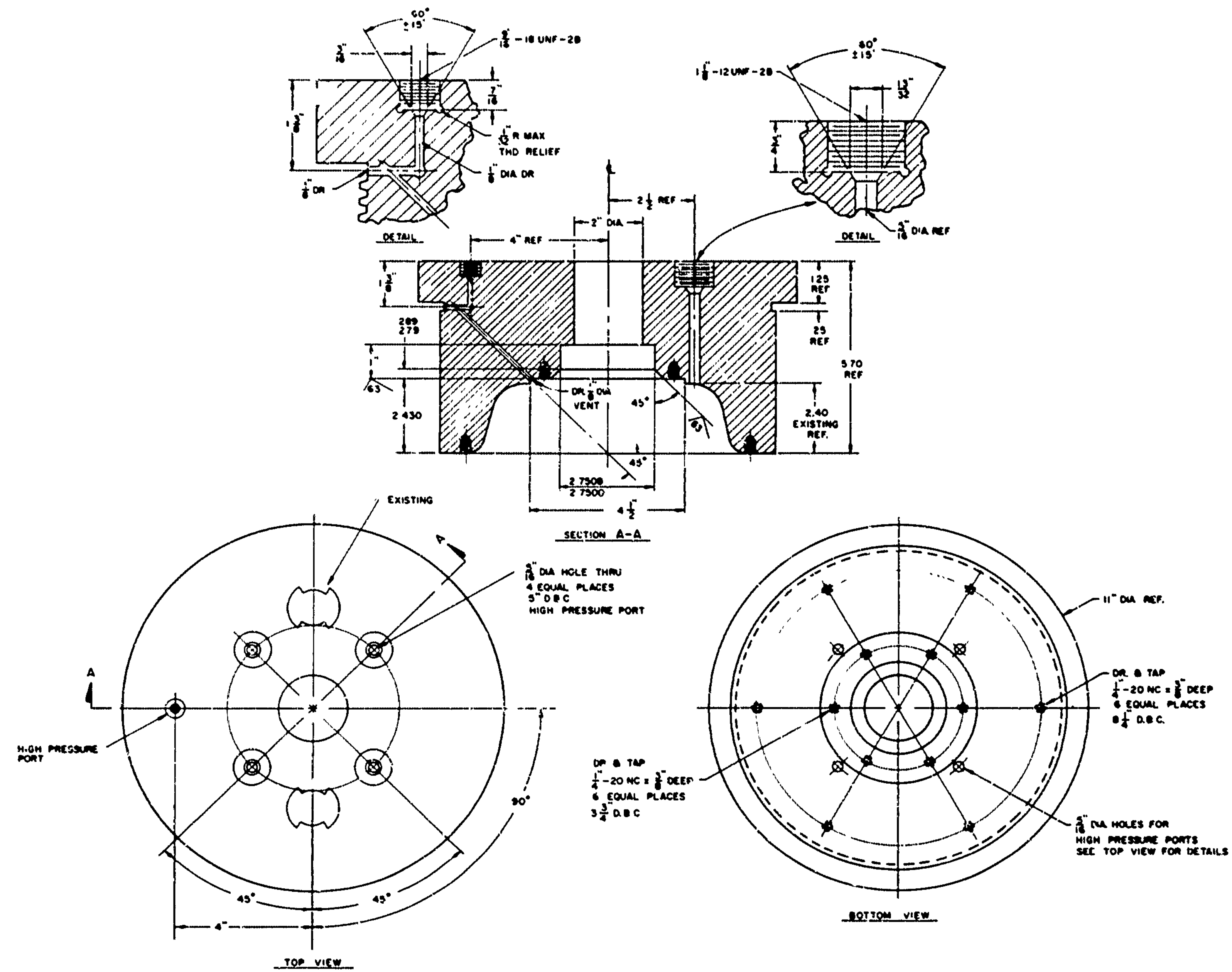


Figure 10. Optical window head plug for Mk-I pressure vessel fabricated

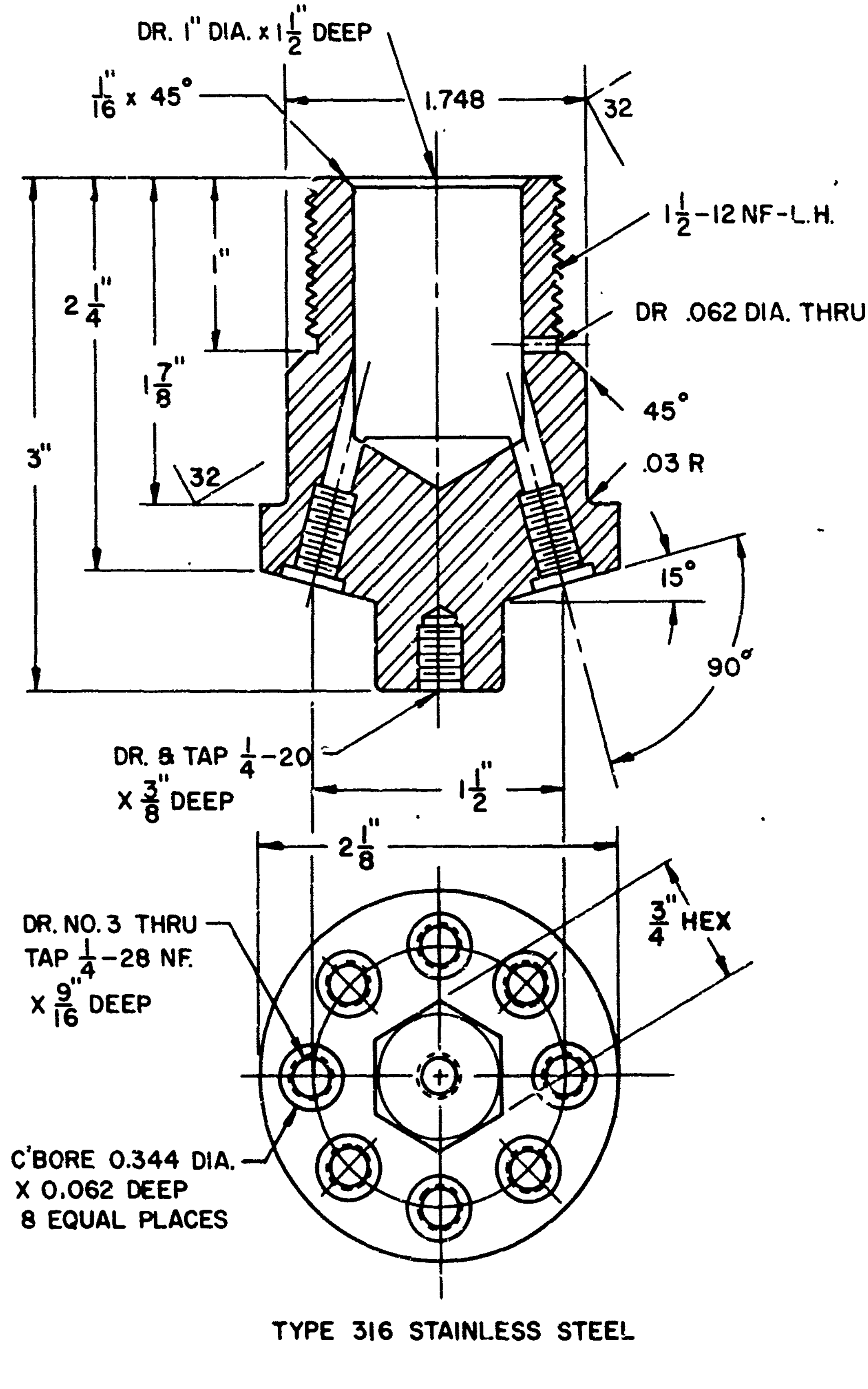


Figure 12. Electrical entry fitting for Mk-I pressure vessel.

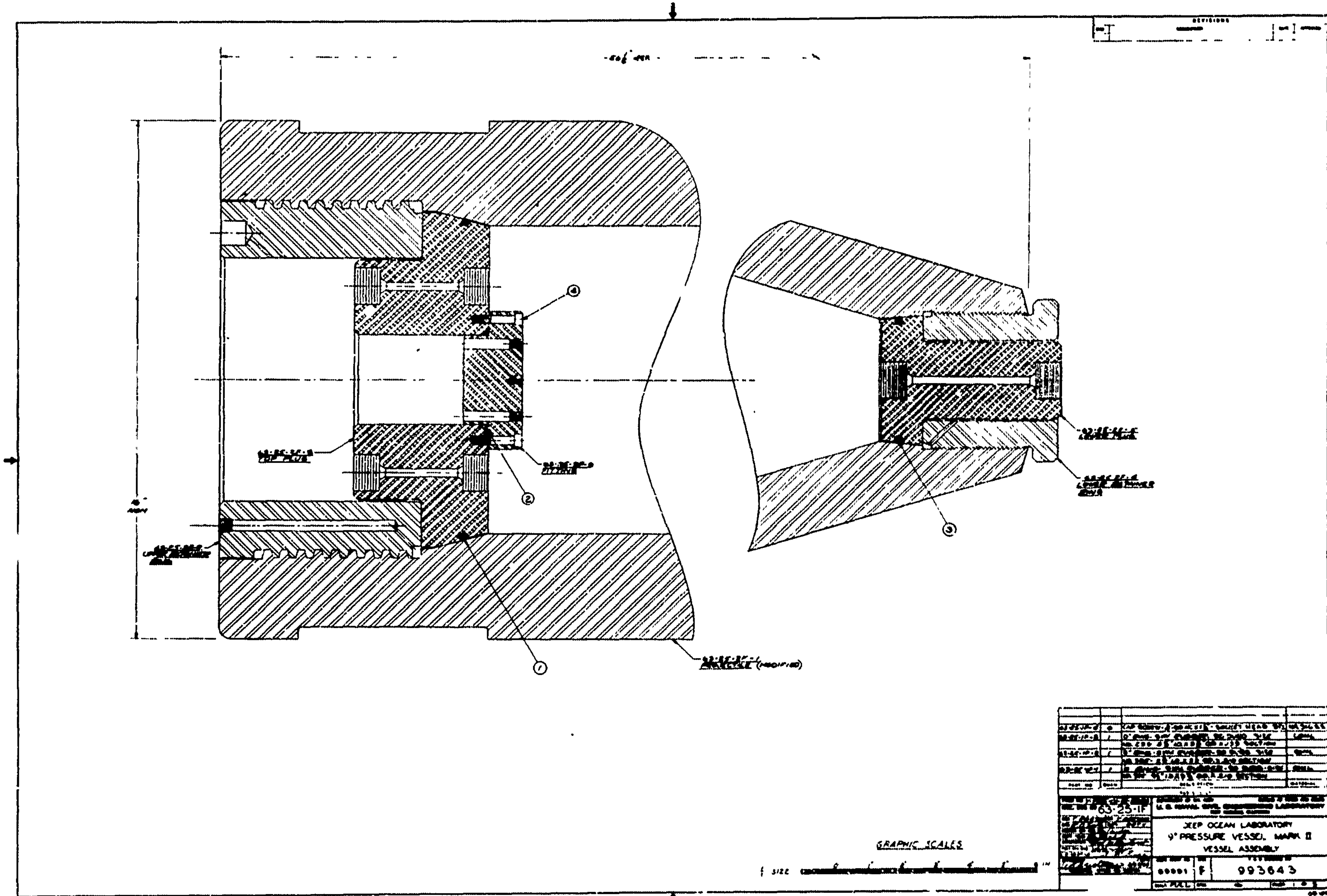


Figure 13. Mk-II pressure vessel general assembly.

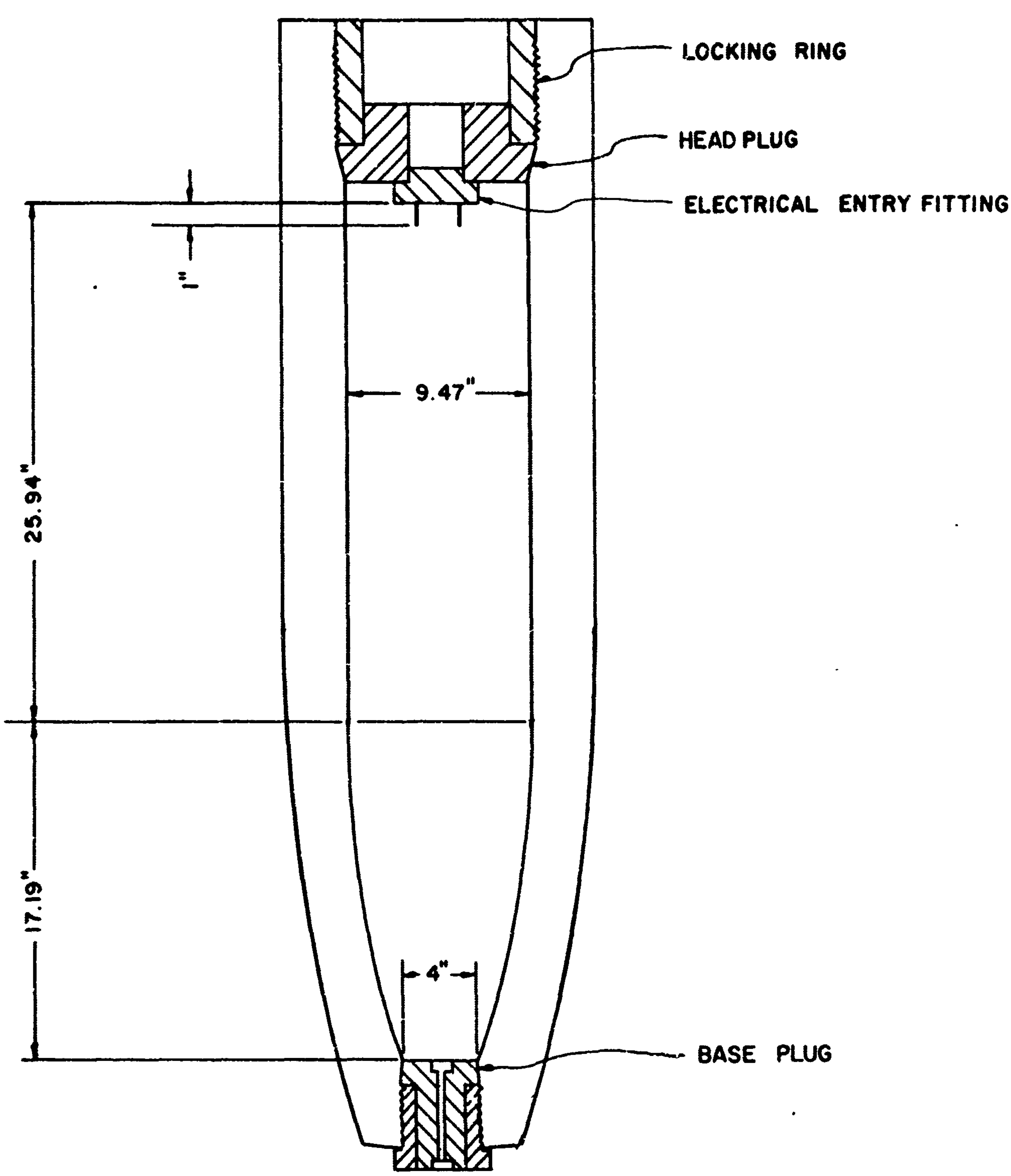


Figure 14. Mk-II pressure vessel internal dimensions.

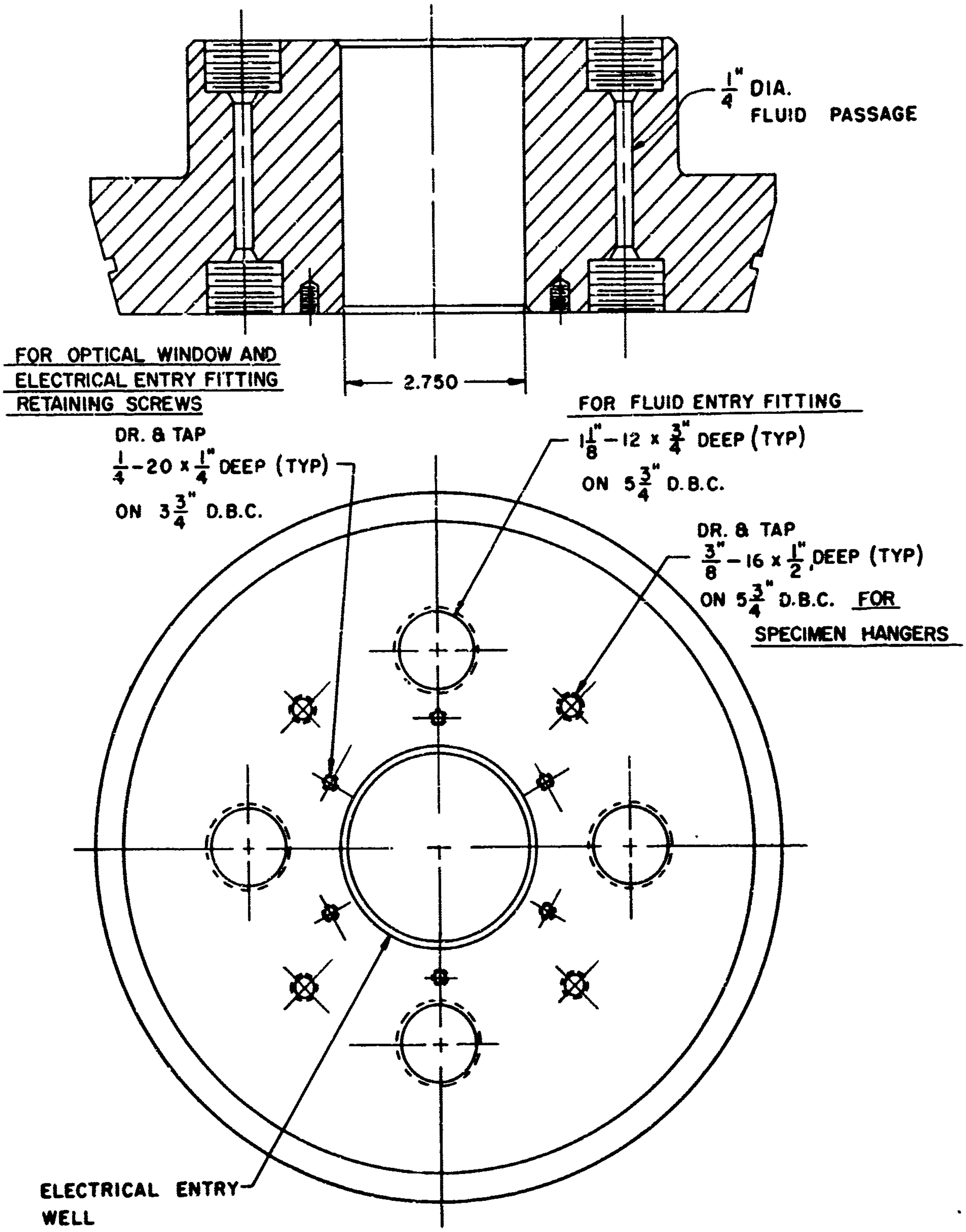


Figure 15. Head plug for Mk-II pressure vessel.

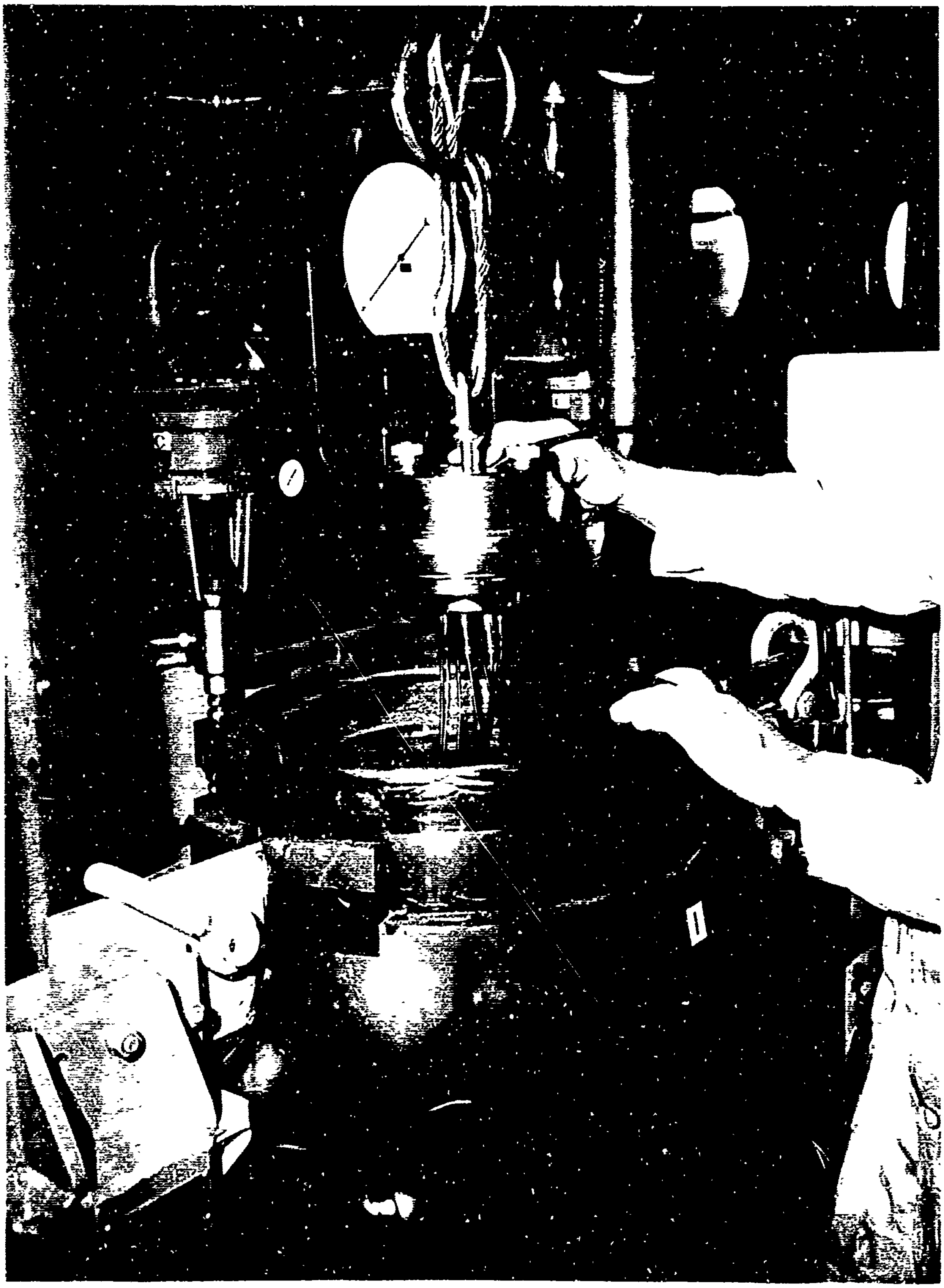


Figure 16. Mk-II head plug with electrical entry fitting in use.

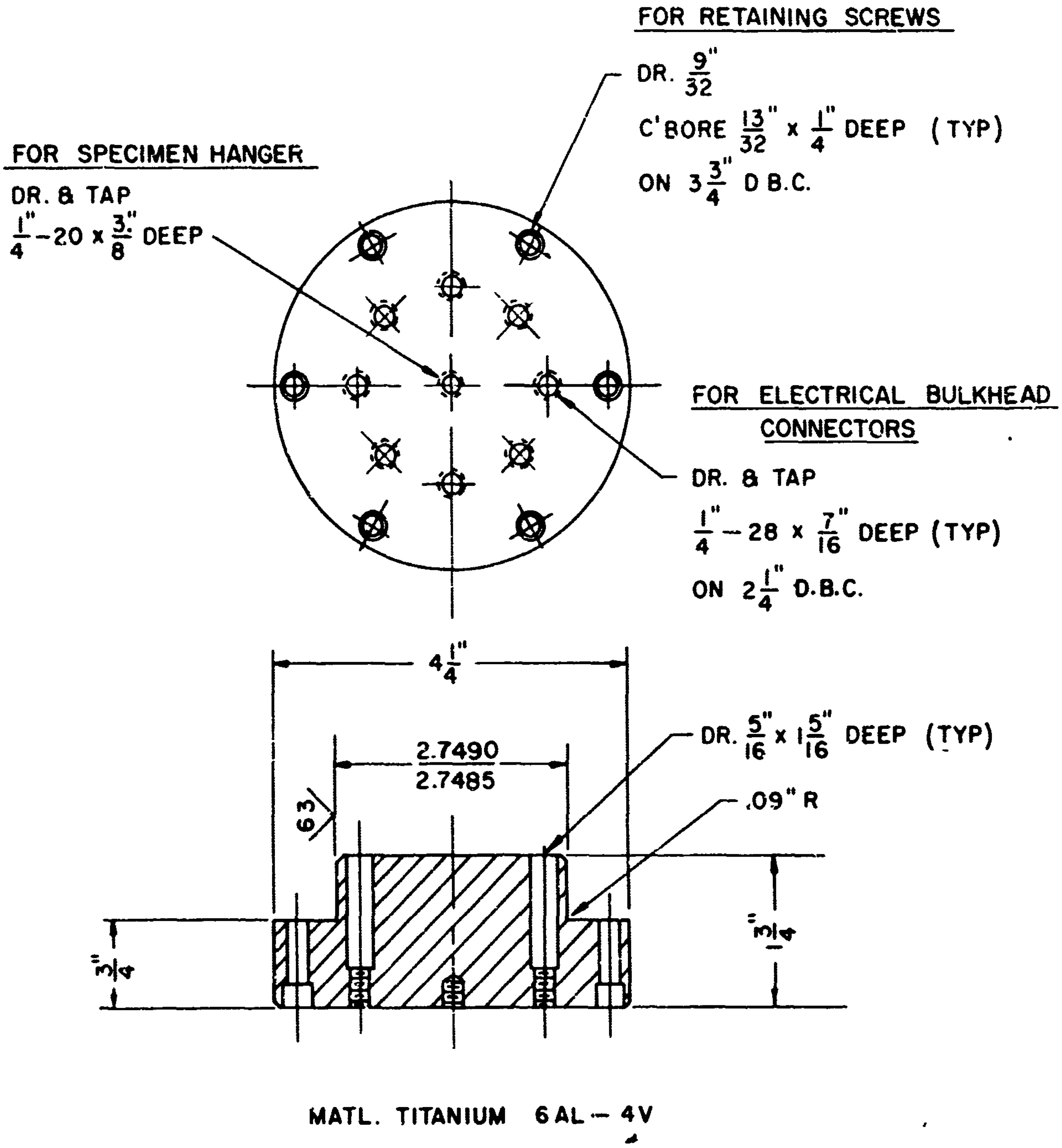
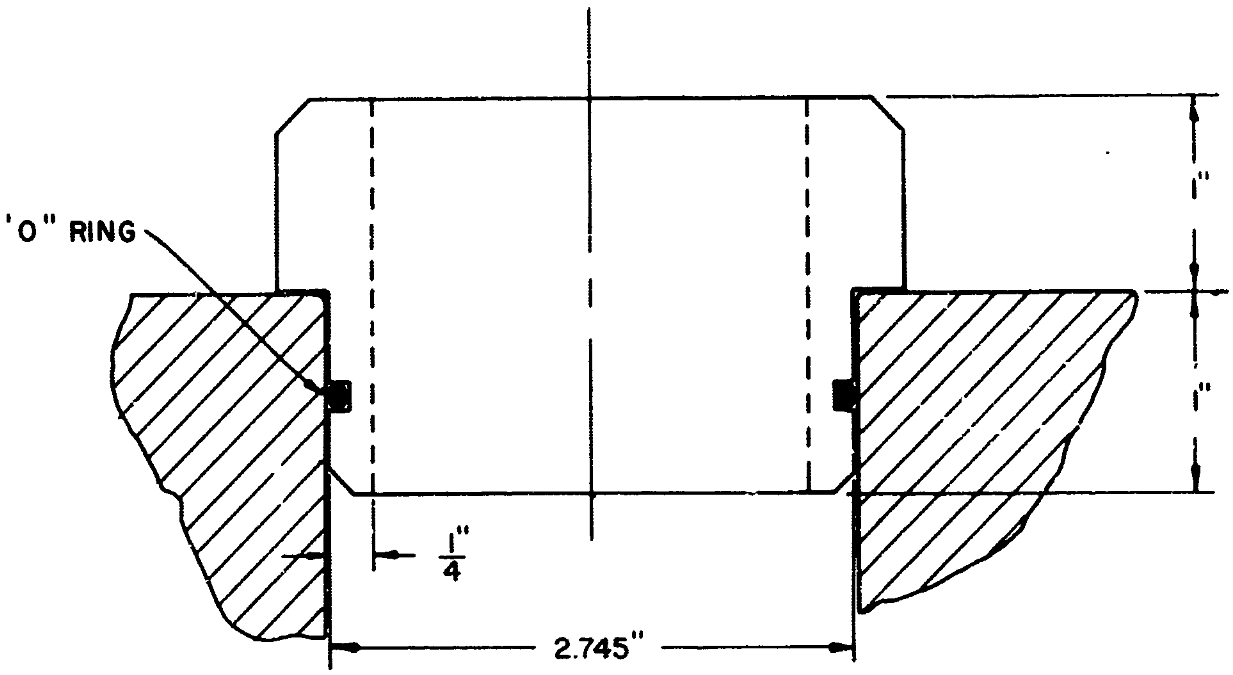


Figure 17. Electrical entry fitting for Mk-II pressure vessel.



FABRICATE FROM PVC PIPE

Figure 18. Electrical entry well dam for Mk-II head plug.

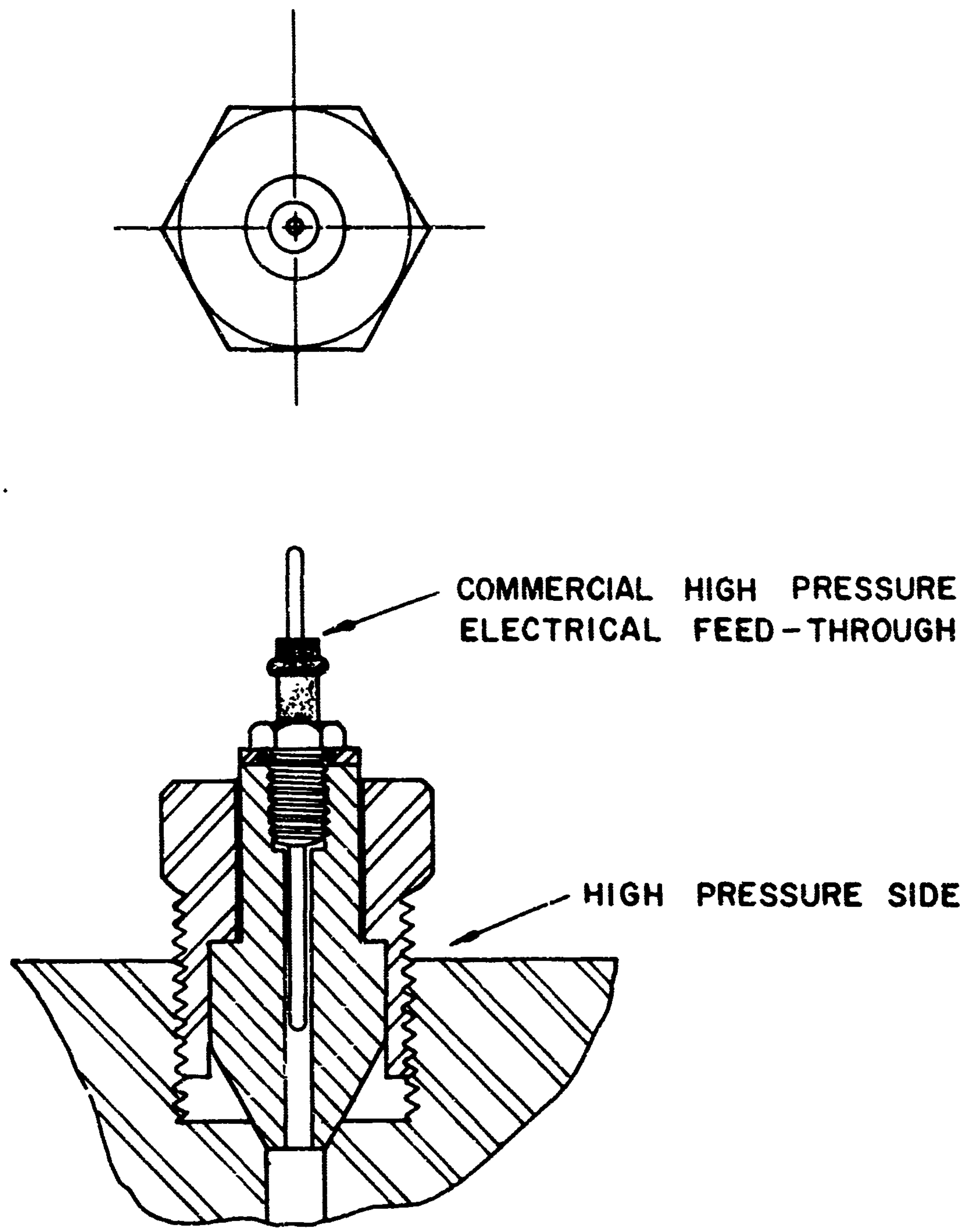


Figure 19. Auxiliary electrical entry fitting fabricated from modified 9/16-inch high pressure plug.

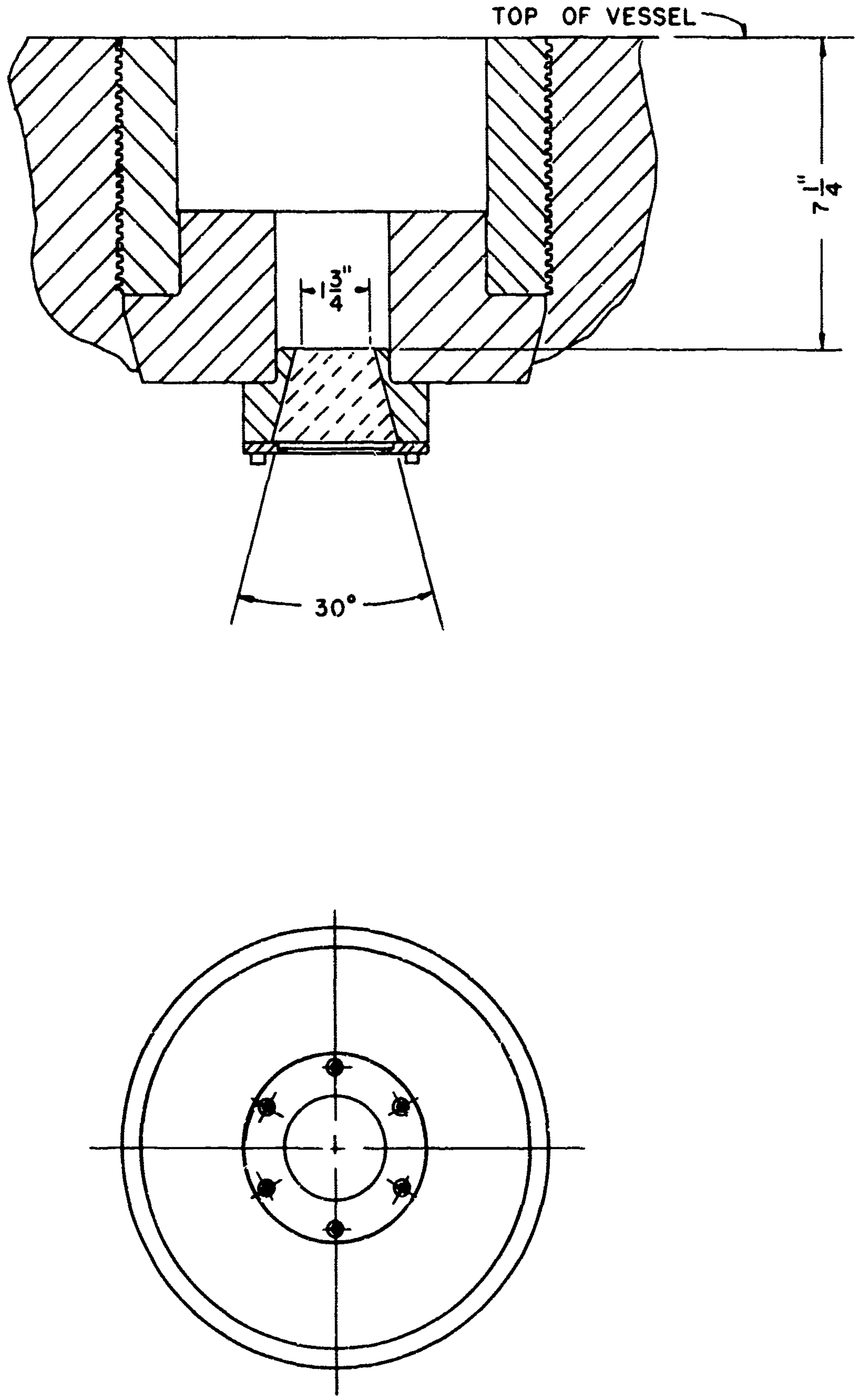


Figure 20. Optical window assembly installed in Mk-II head plug.

Figure 21. Optical window assembly.

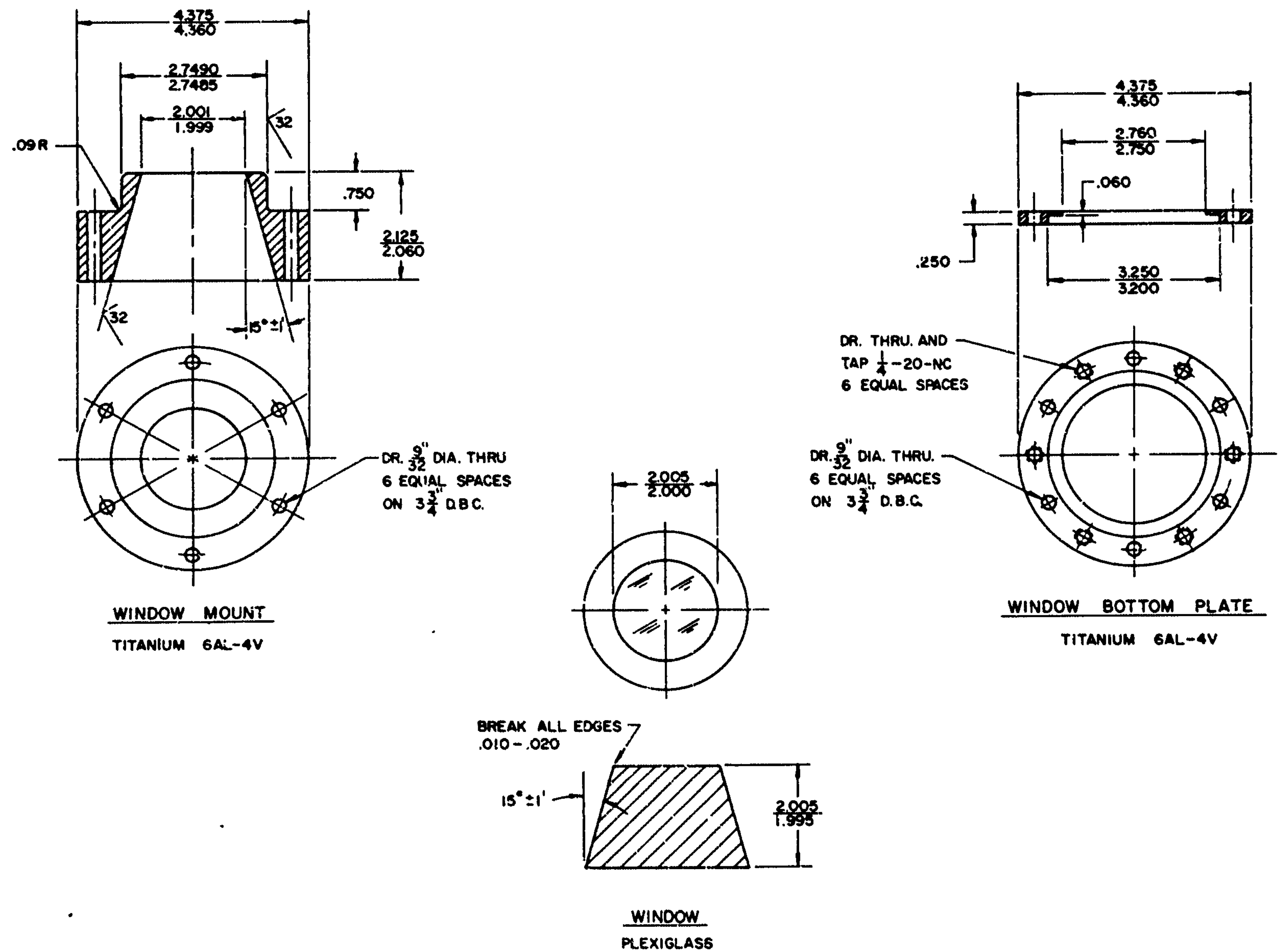


Figure 22. Optical window assembly construction details.

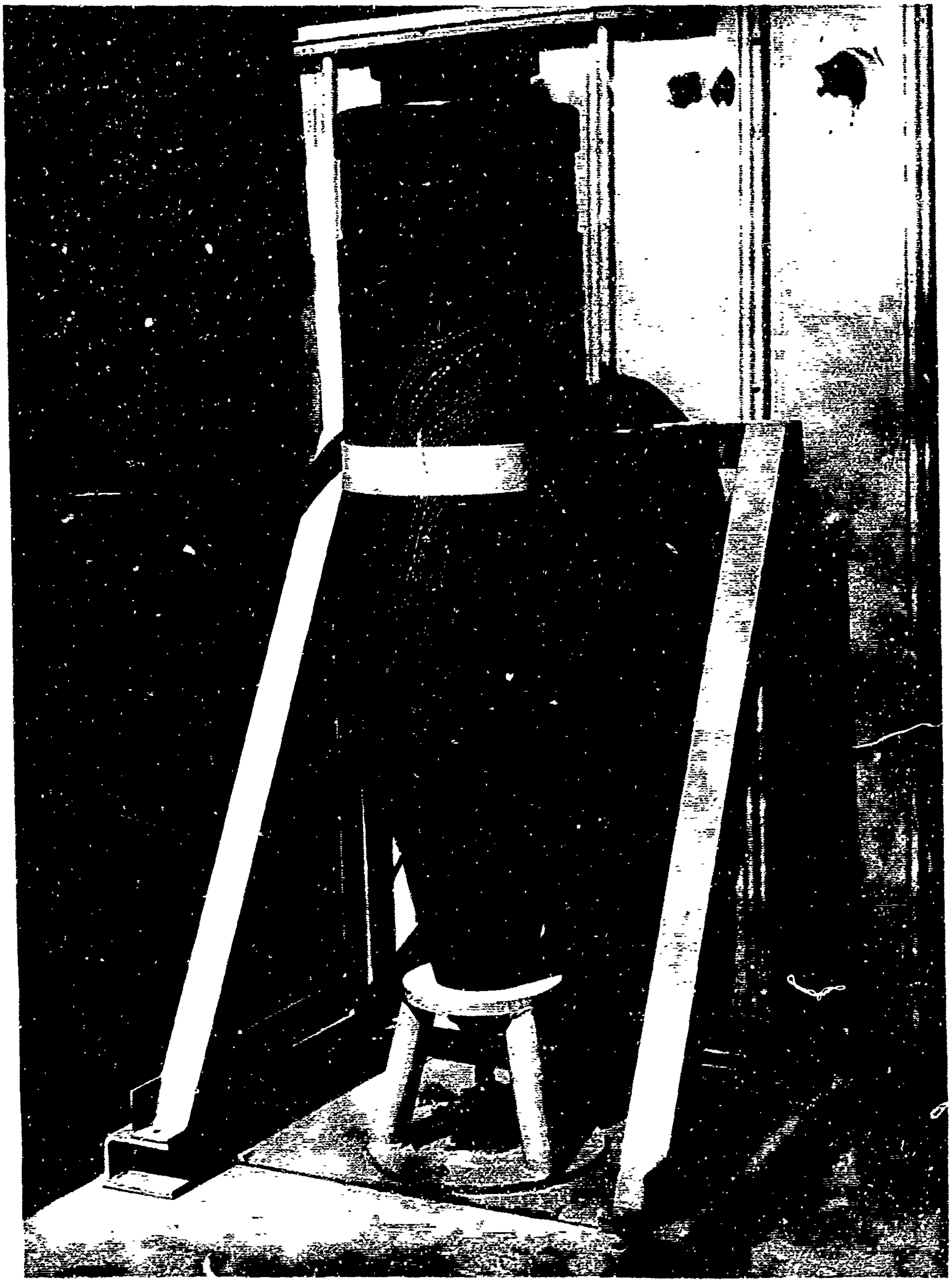


Figure 23. Mk-I pressure vessel in support frame with fork-lift truck adaptor base.

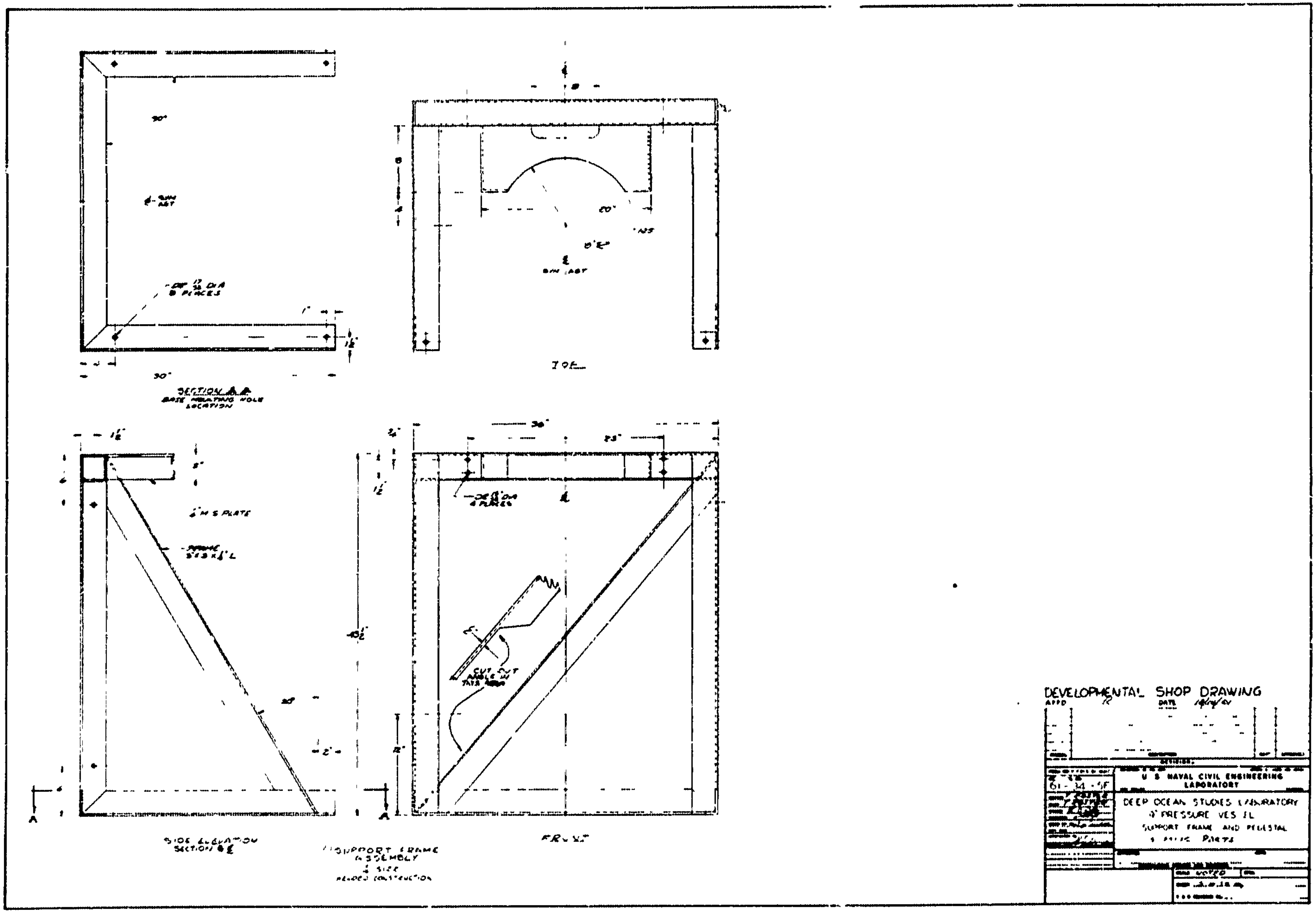


Figure 24. Mk-I pressure vessel support frame construction details.

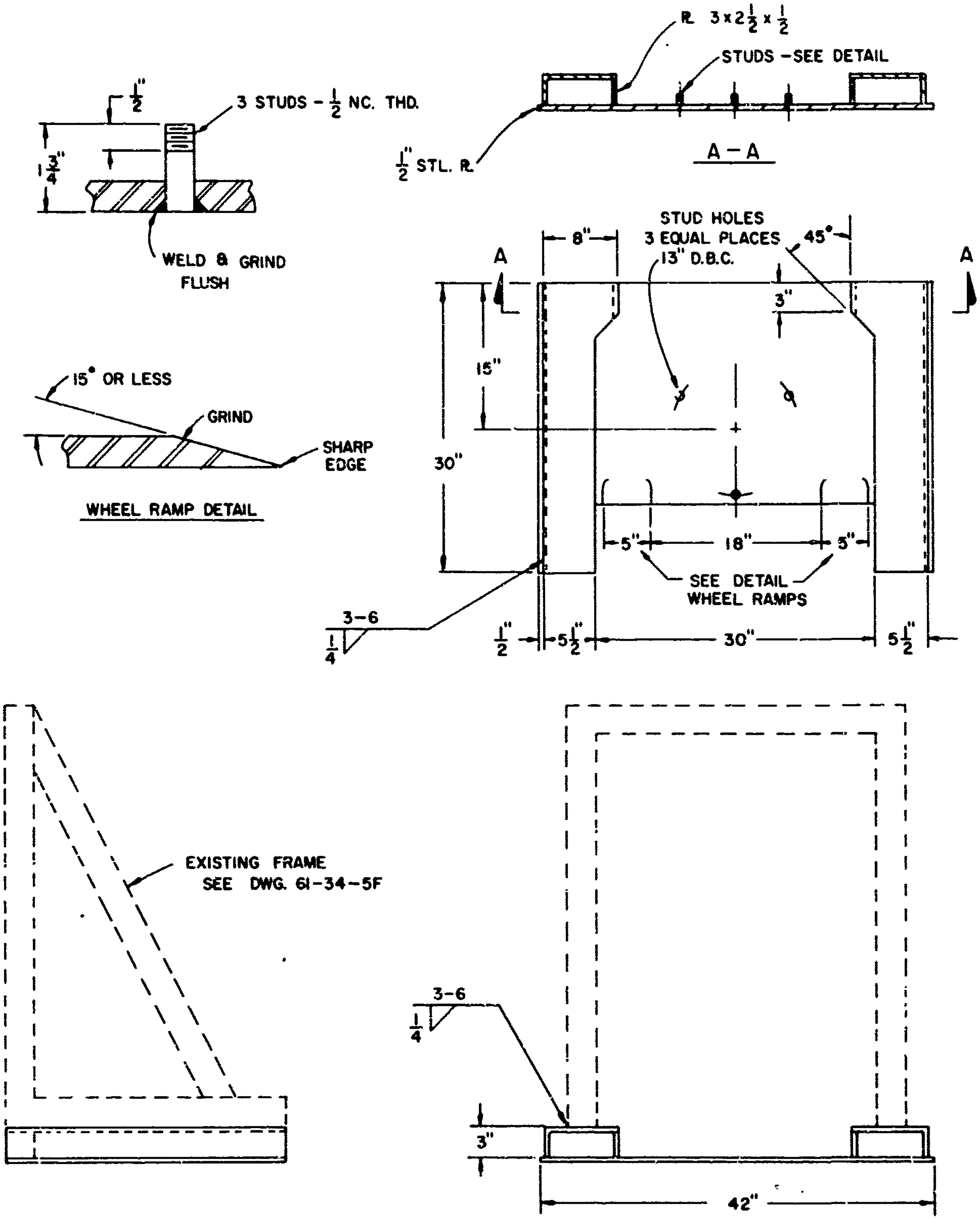


Figure 25. Fork-lift truck adaptor base construction details.

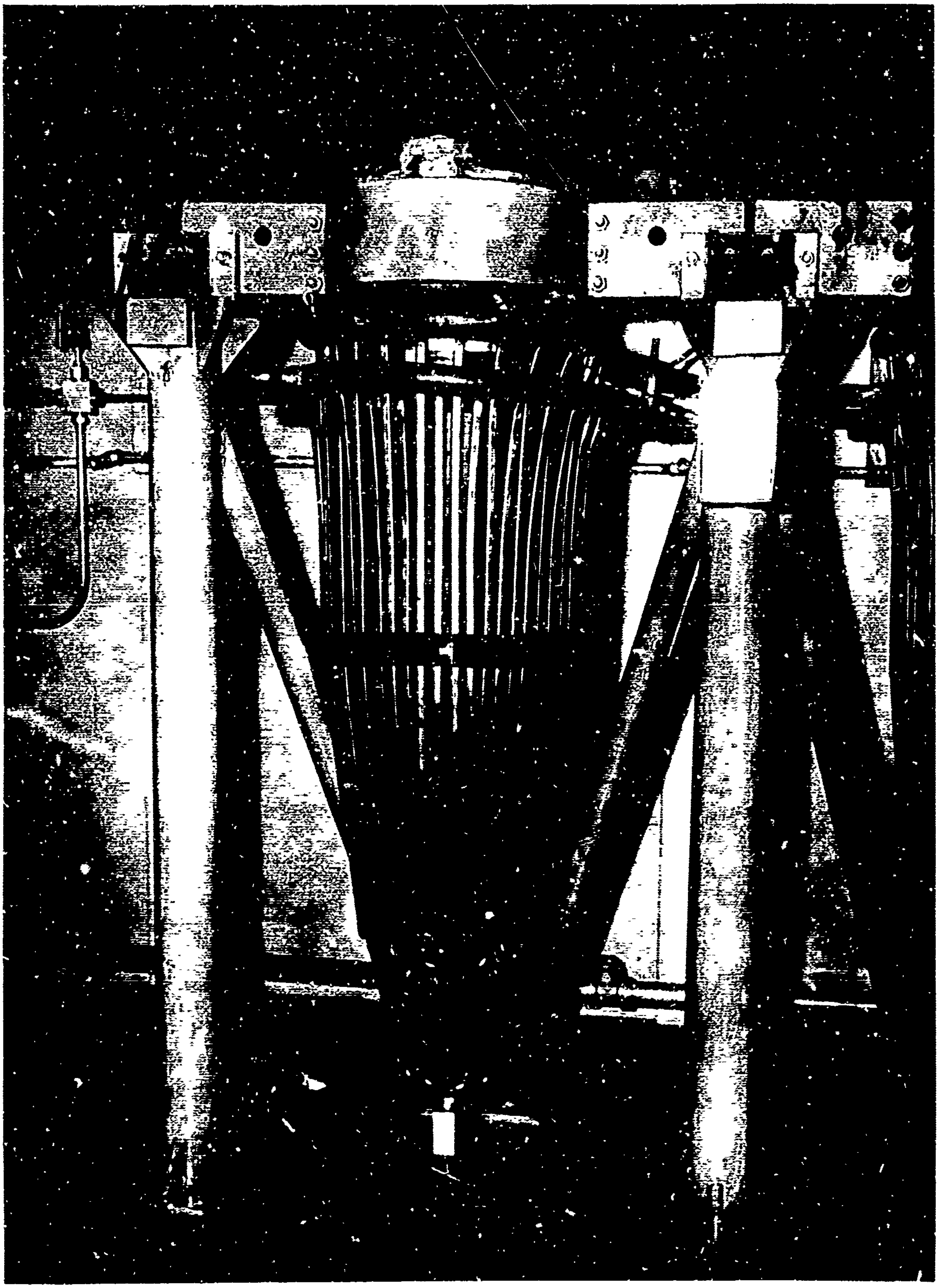


Figure 26. Mk-II pressure vessel support frame. Cooling coils are shown before application of insulating jacket.

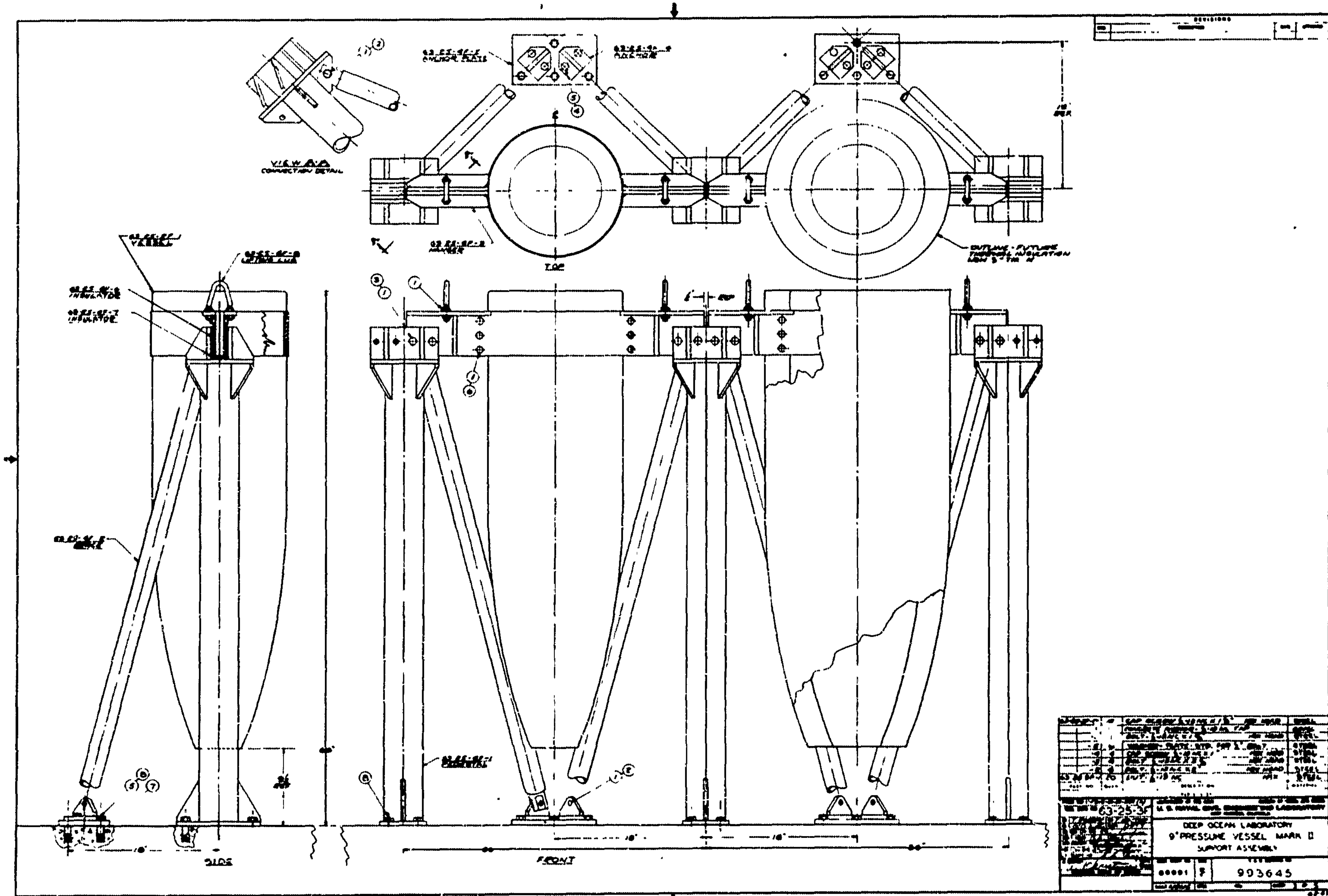


Figure 27. Mk-II pressure vessel support frame general assembly.

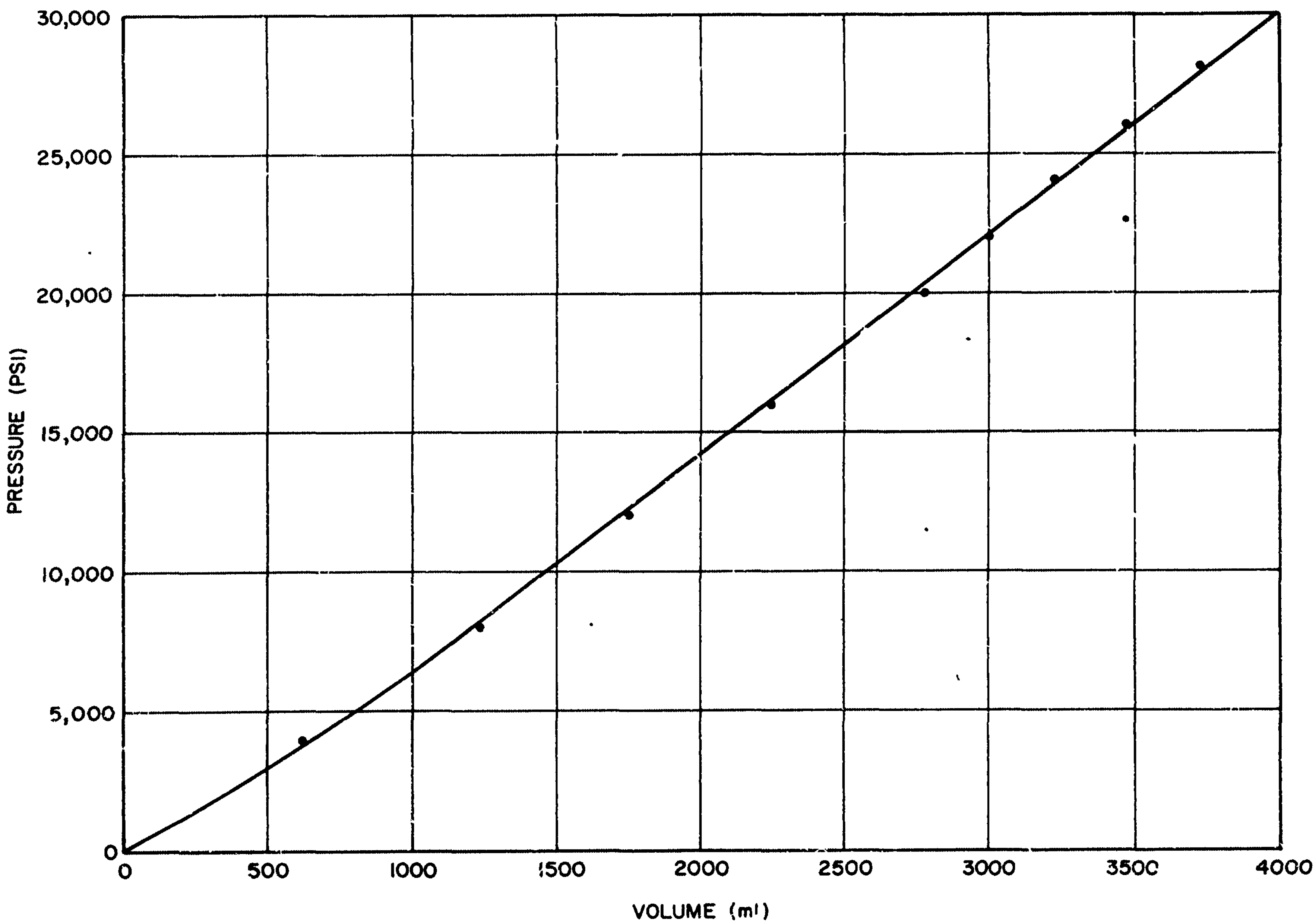


Figure 29. Volume Vs Pressure plot showing the amount of water which must be pumped into a full Mk-I pressure vessel to increase pressure from 0 to 28,000 psi.

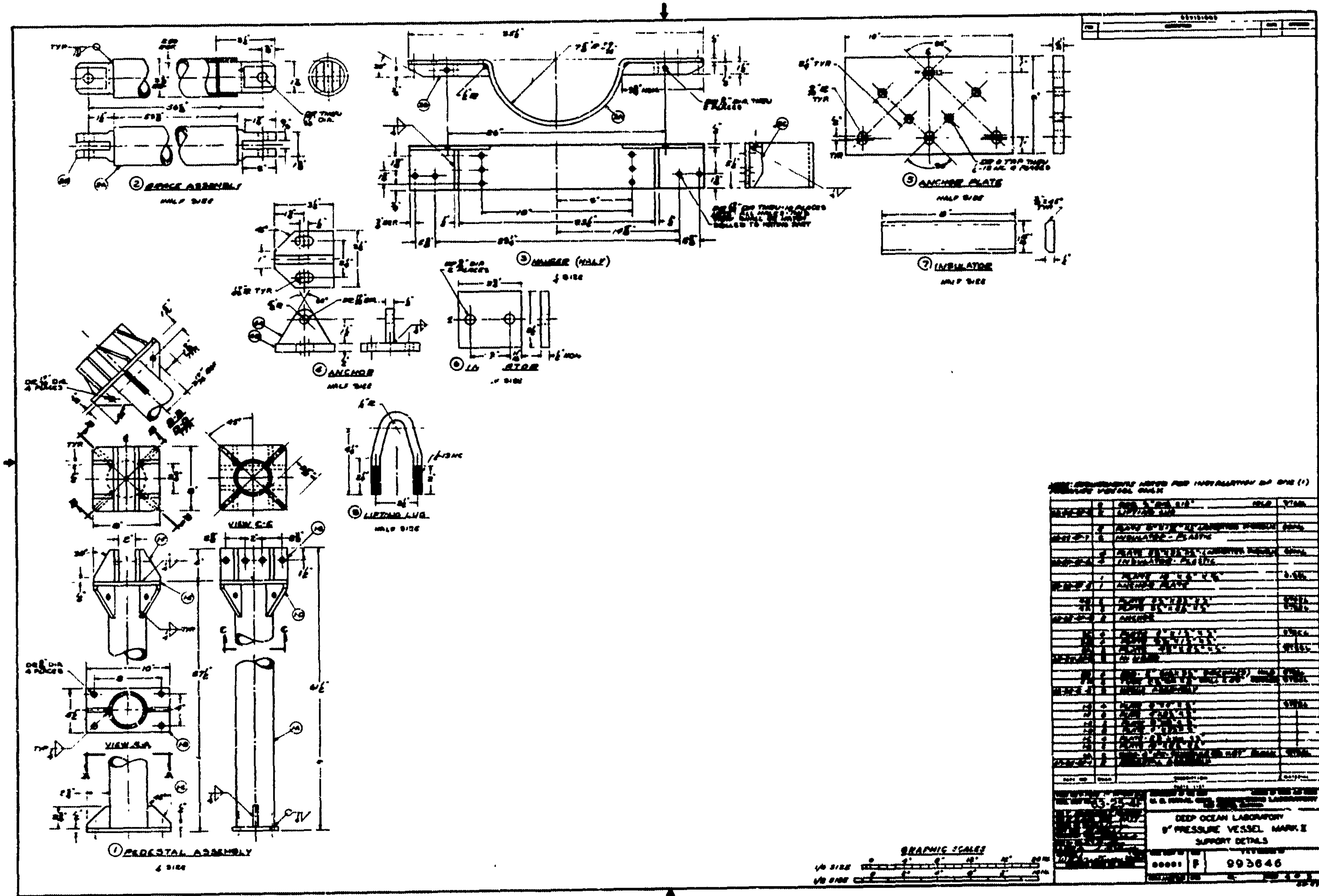


Figure 28. Mk-II pressure vessel support frame construction details.

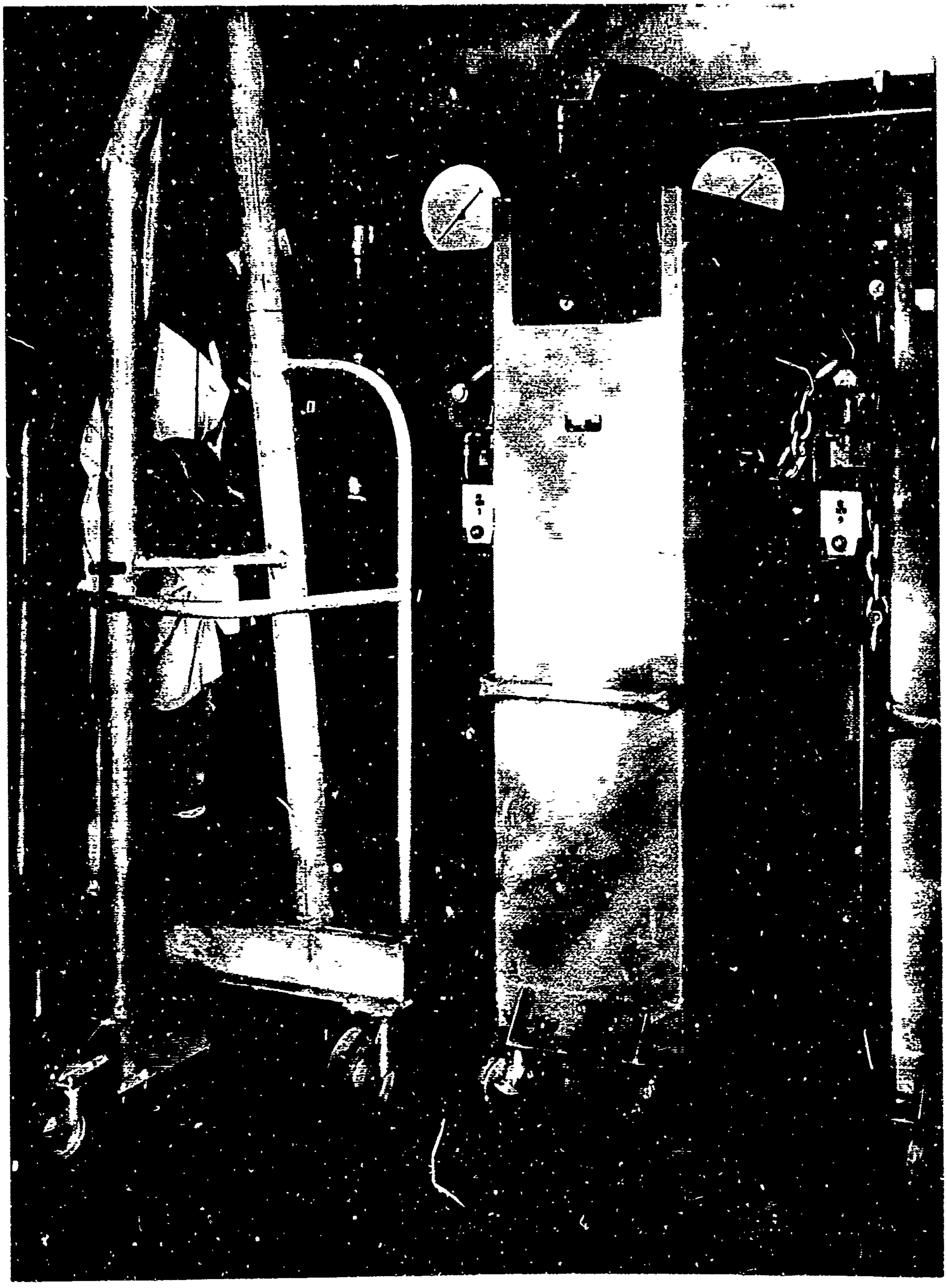


Figure 30. Safety shields in use.

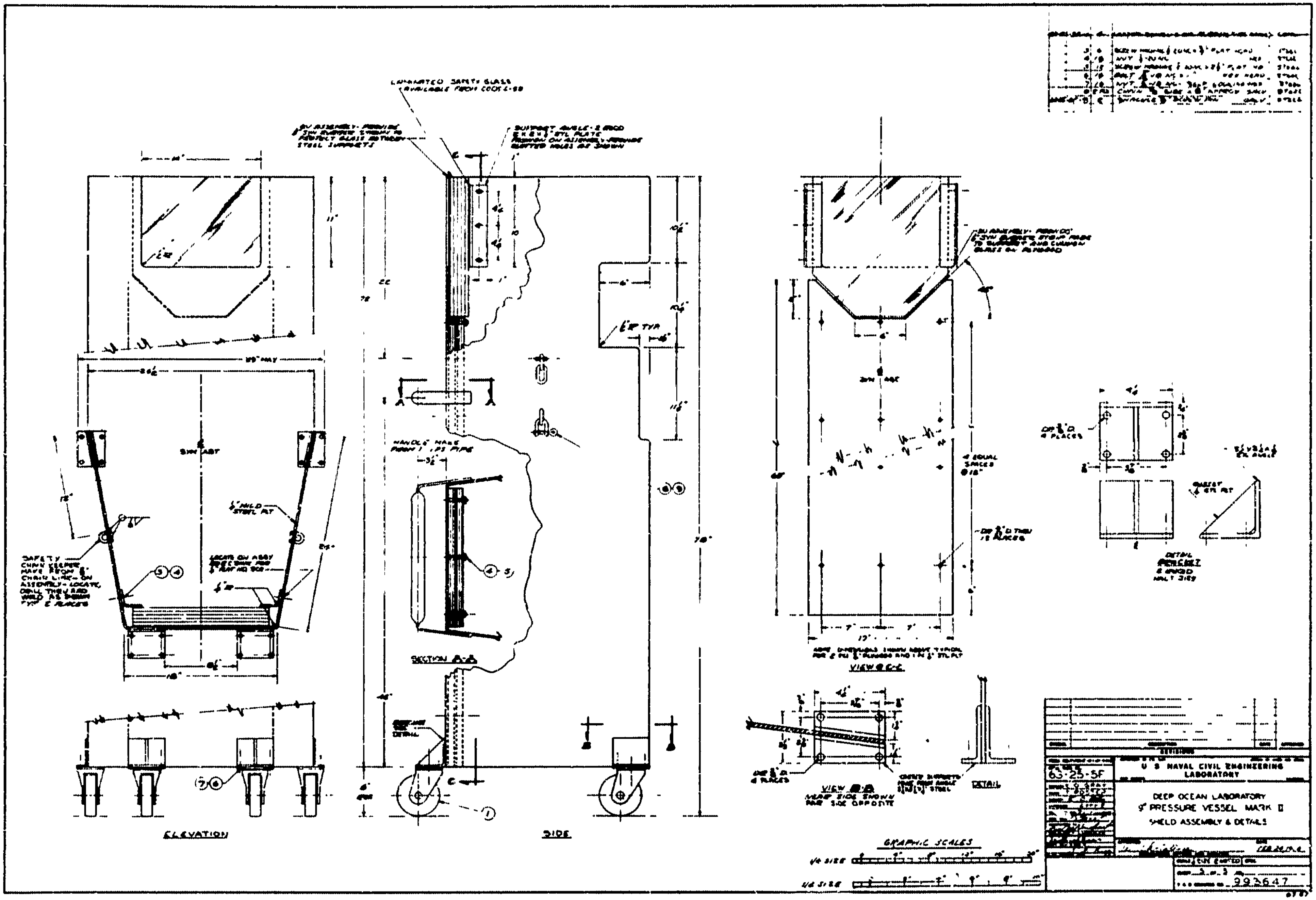


Figure 31. Safety shield construction details.

Figure 32. Safety shield with overhead blast cover installed.

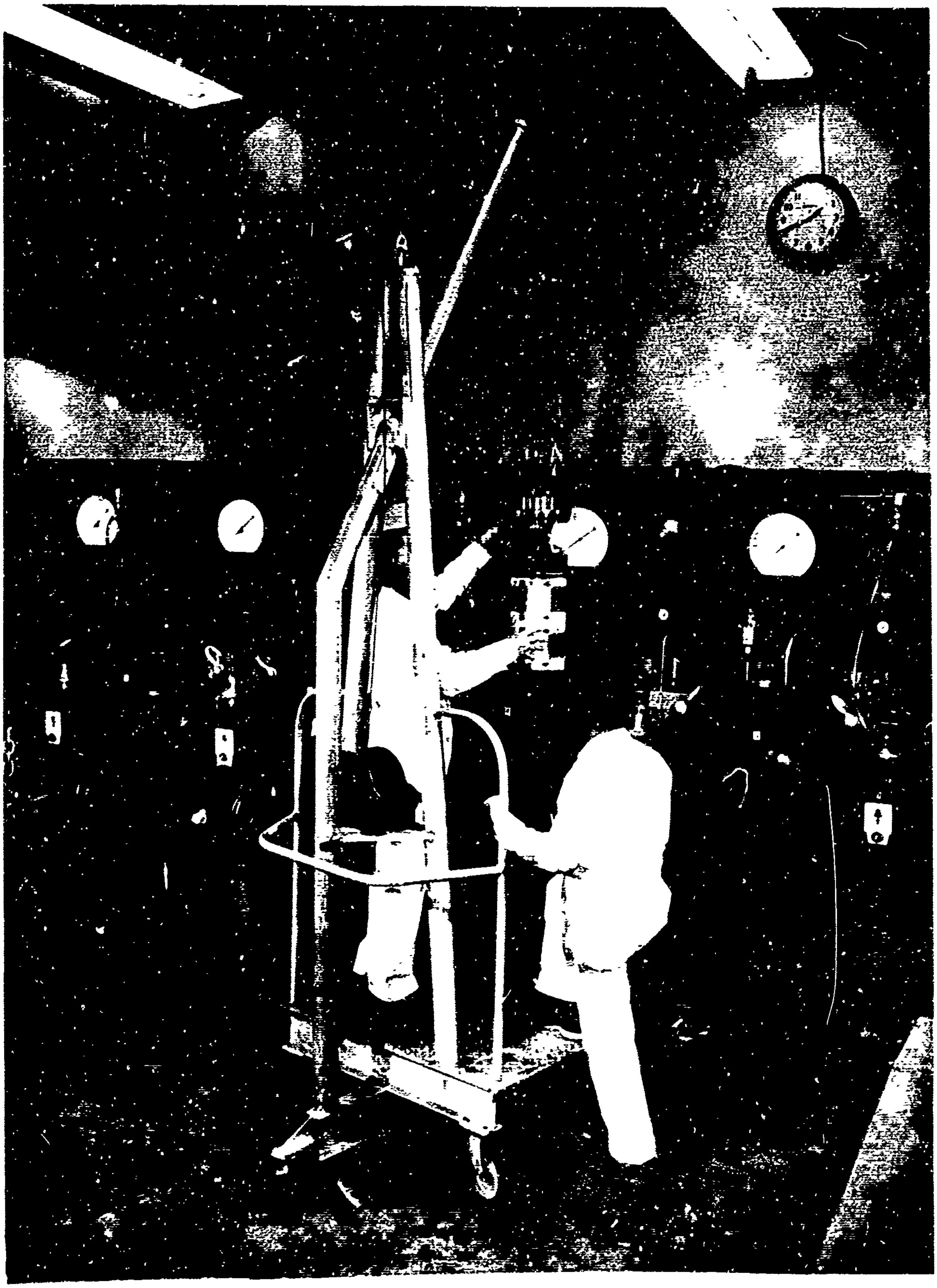


Figure 33. Pressure vessel service hoist in use.

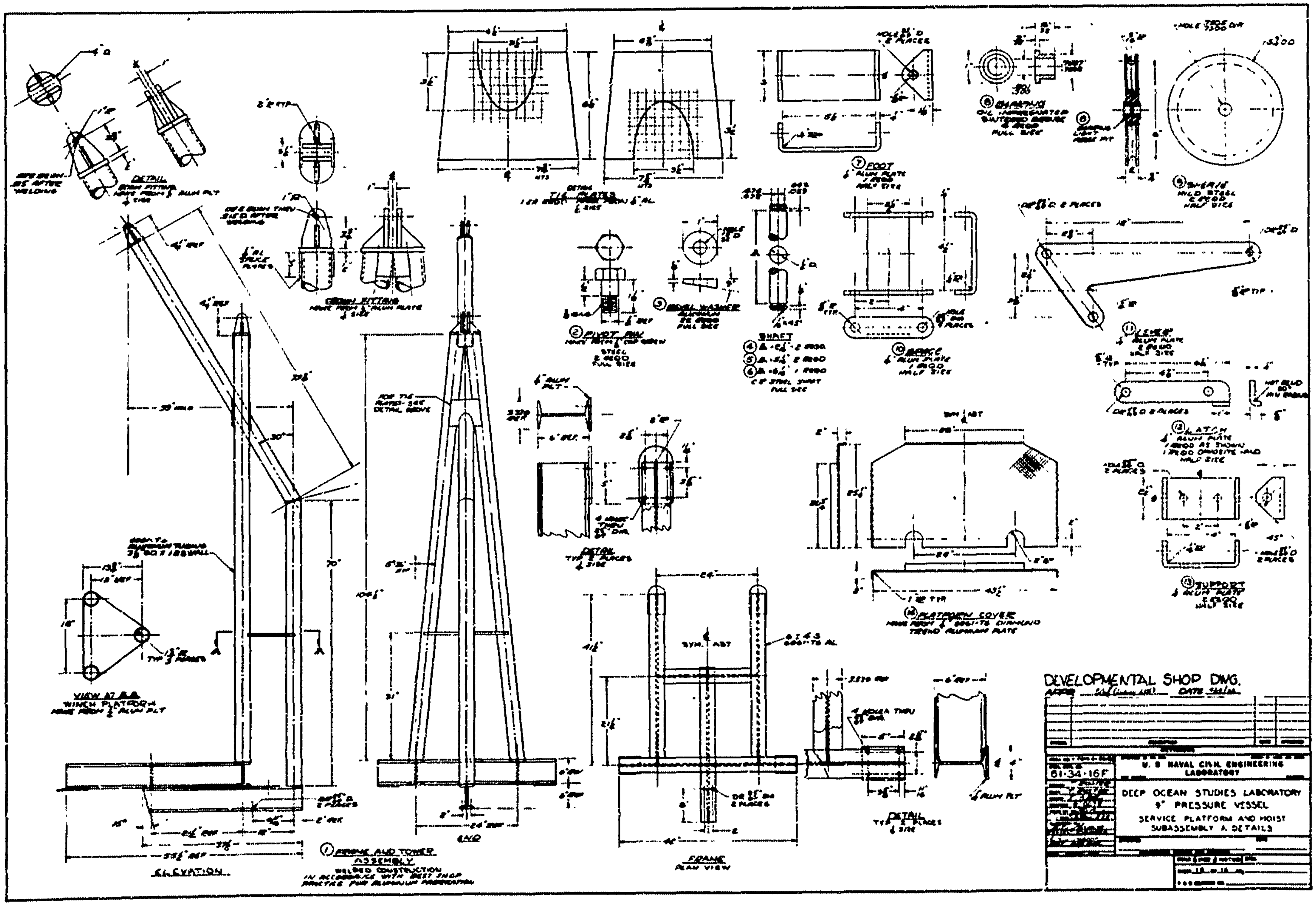


Figure 35. Service hoist construction details.

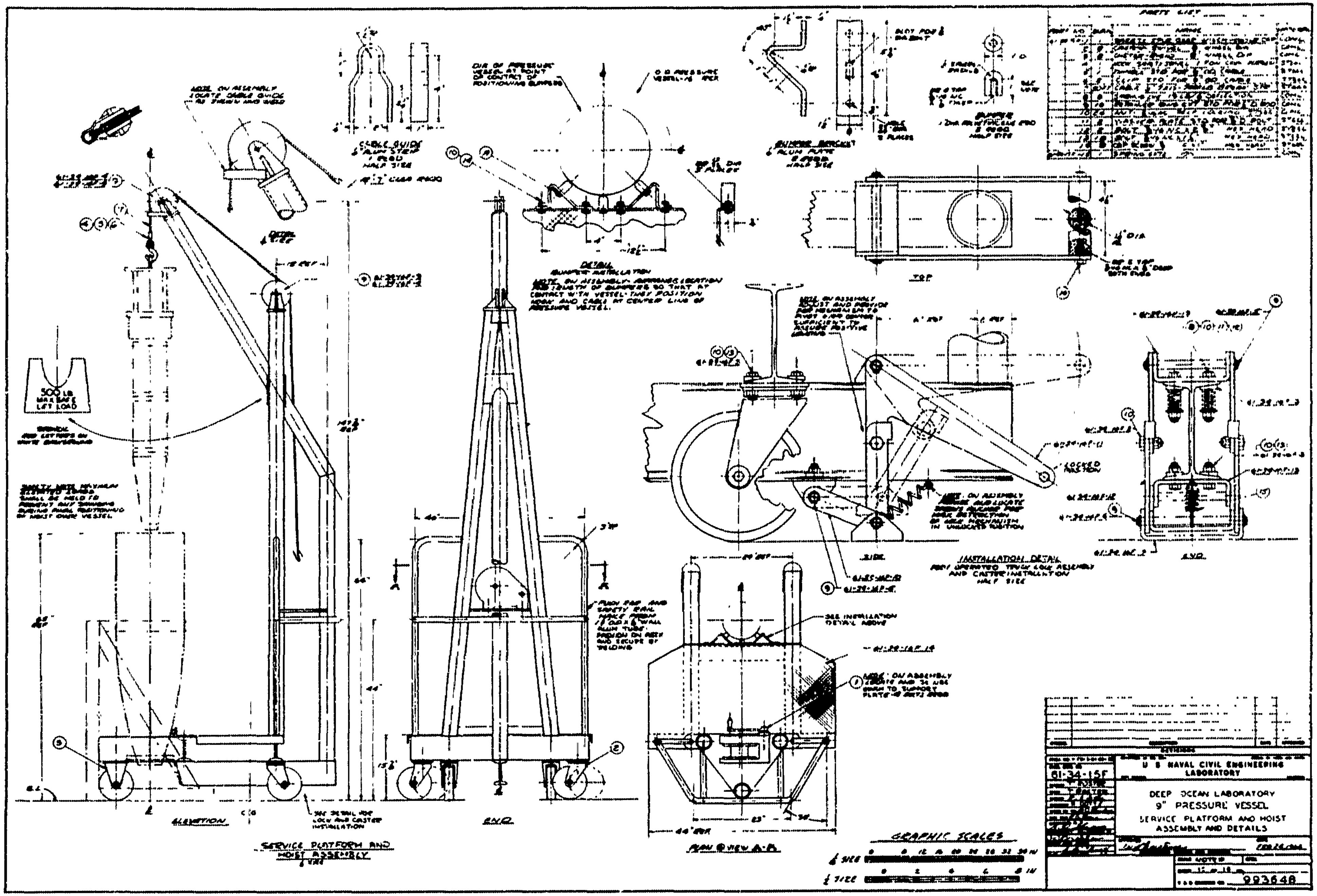


Figure 34. Service hoist general assembly.

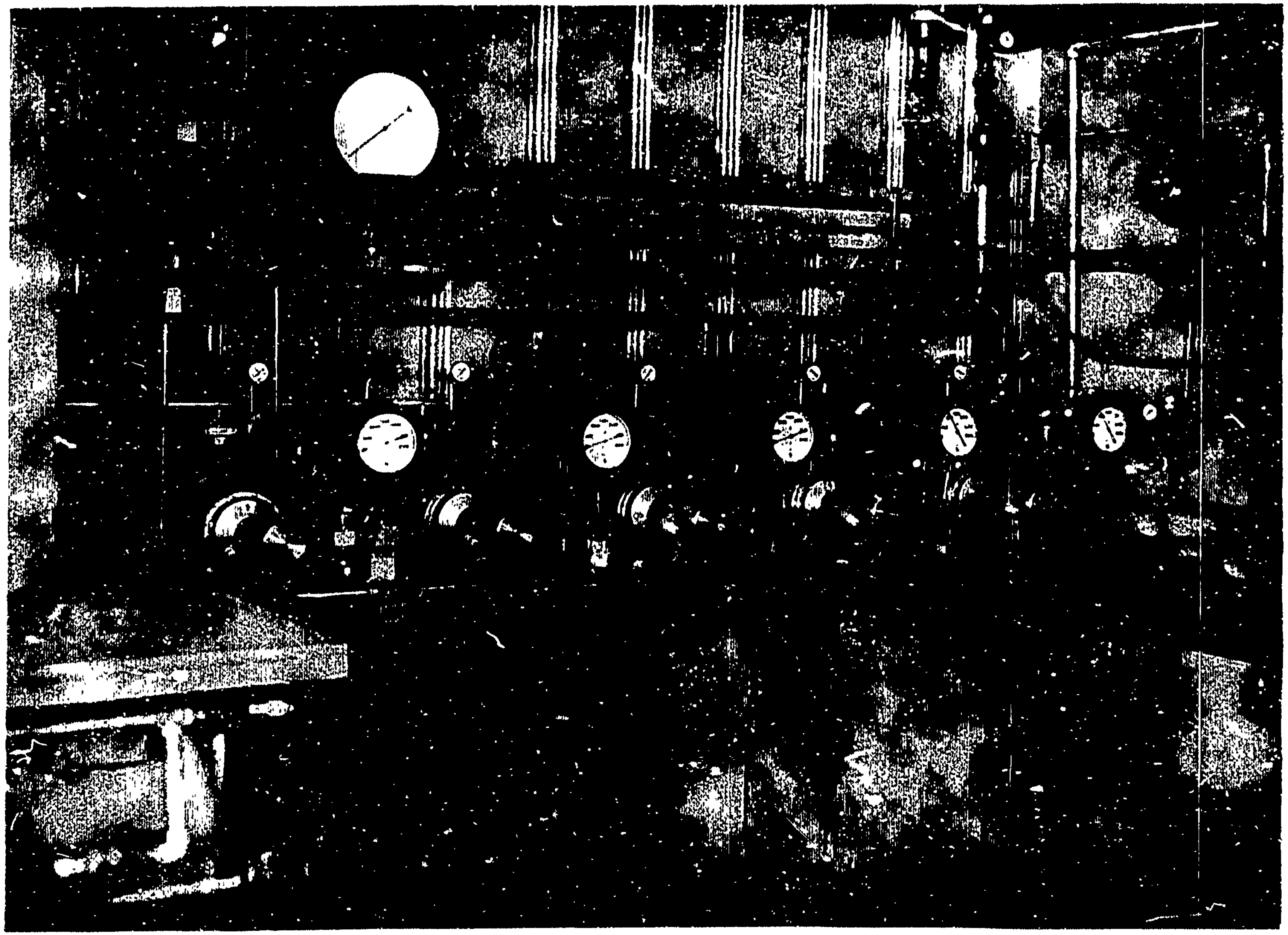


Figure 36. High pressure pumping system utilizing five air driven 25,000 psi pumps.

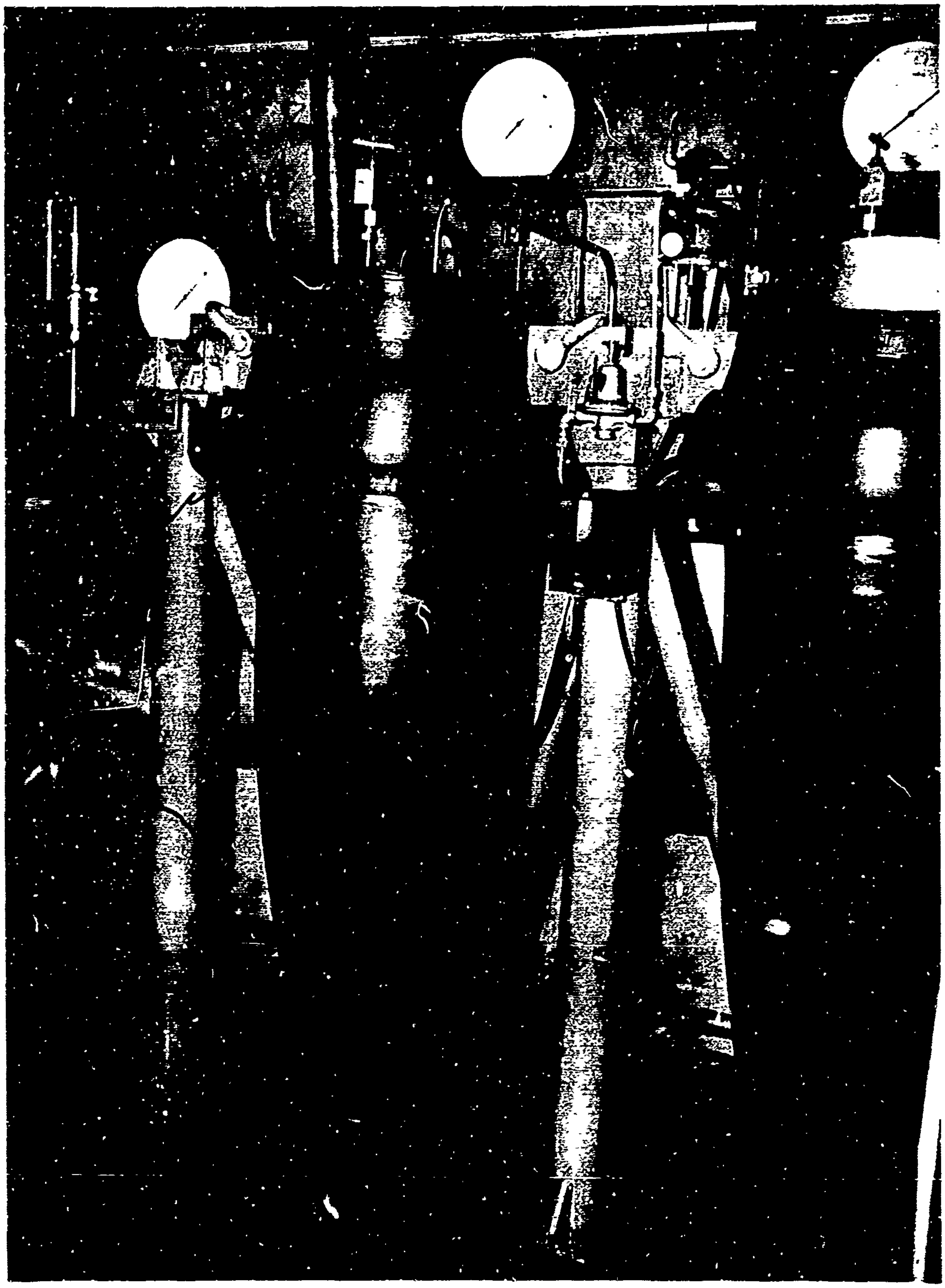


Figure 37. Mk-II pressure vessel refrigeration connections and insulation.

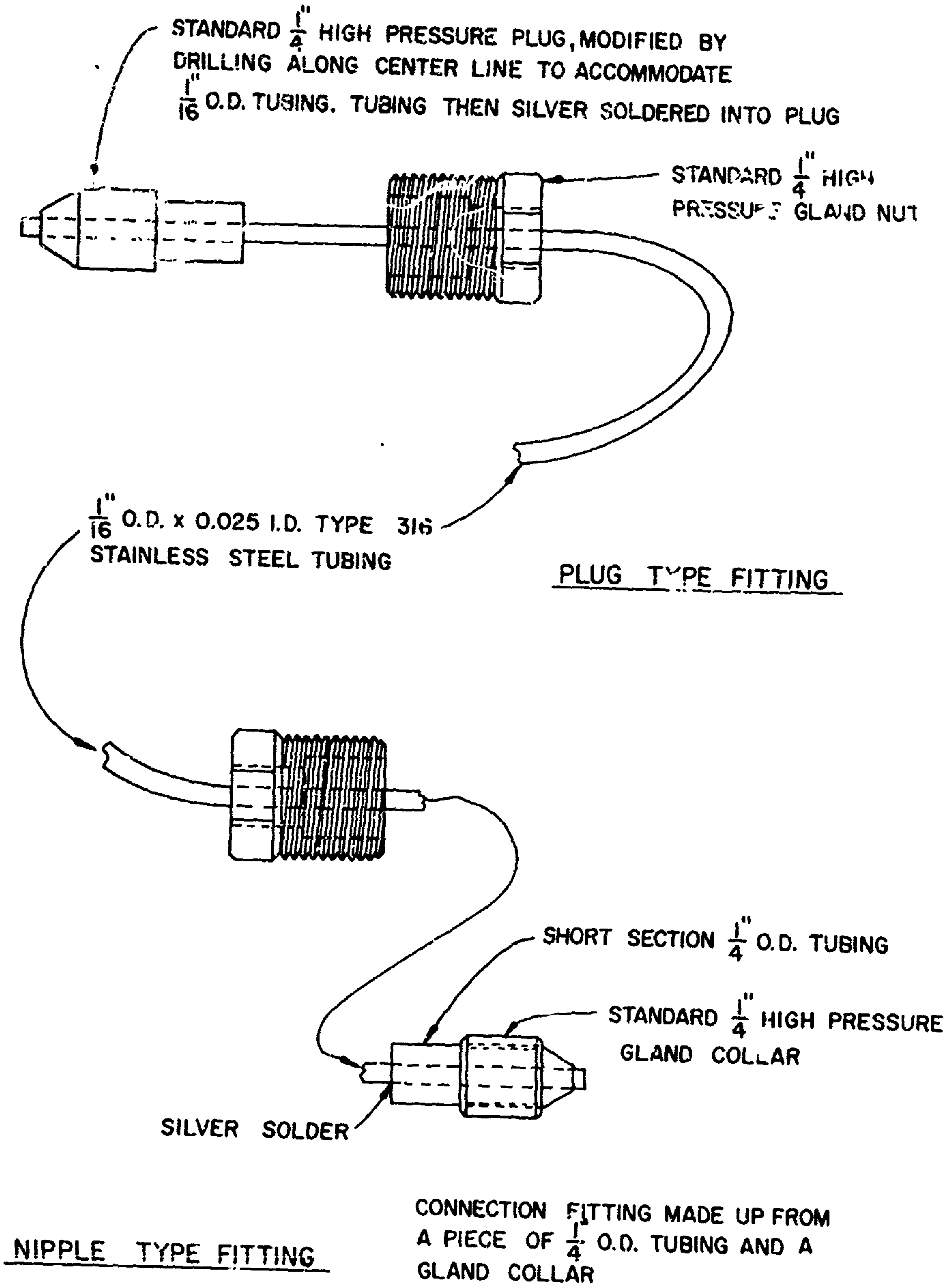


Figure 38. "Flexible" 1/16-inch o.d. high pressure tubing and connection system.

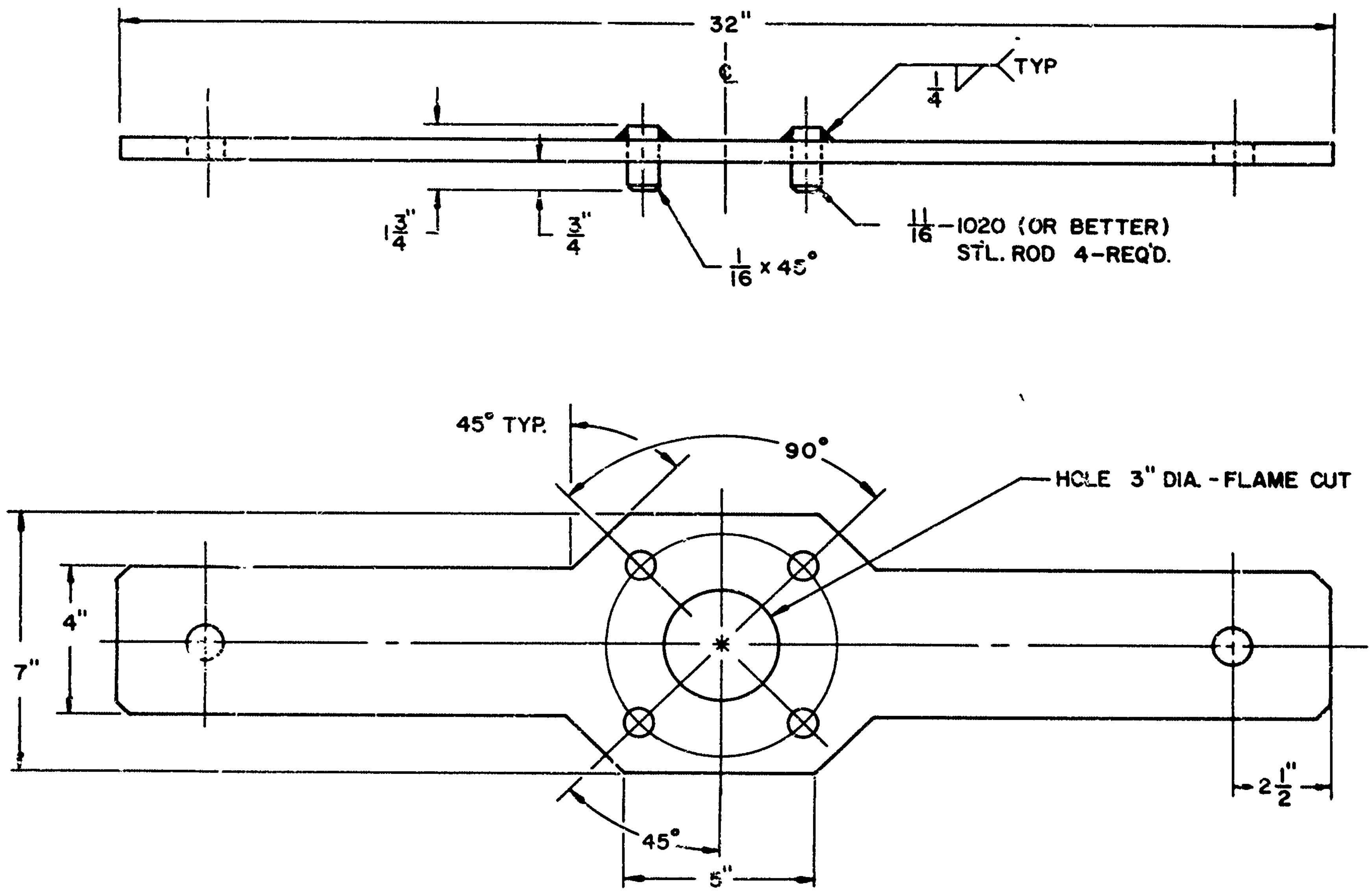


Figure 39. Mk-I head plug "breakout" wrench.

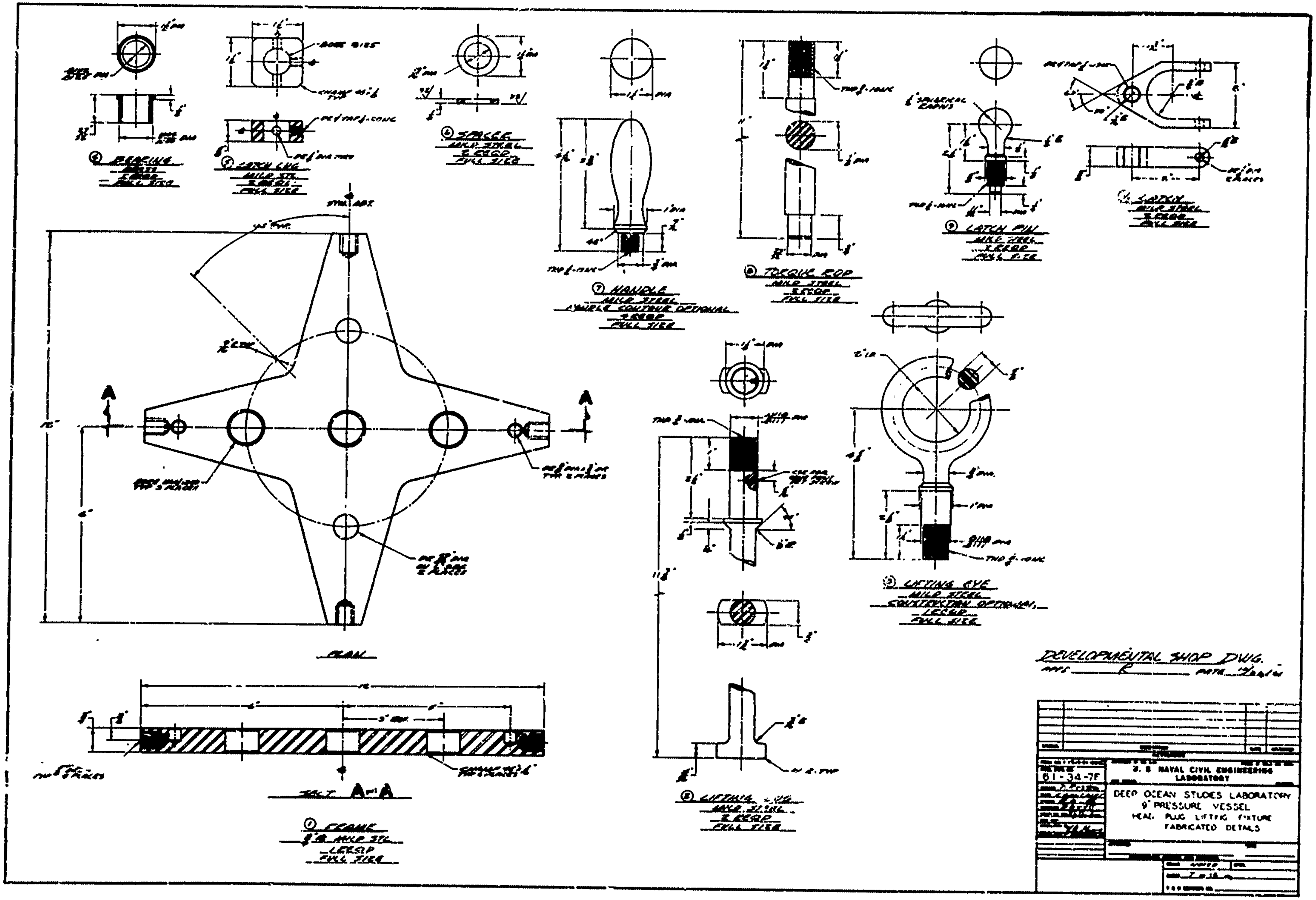


Figure 41. Mk-I head plug turning and lifting device, construction details.

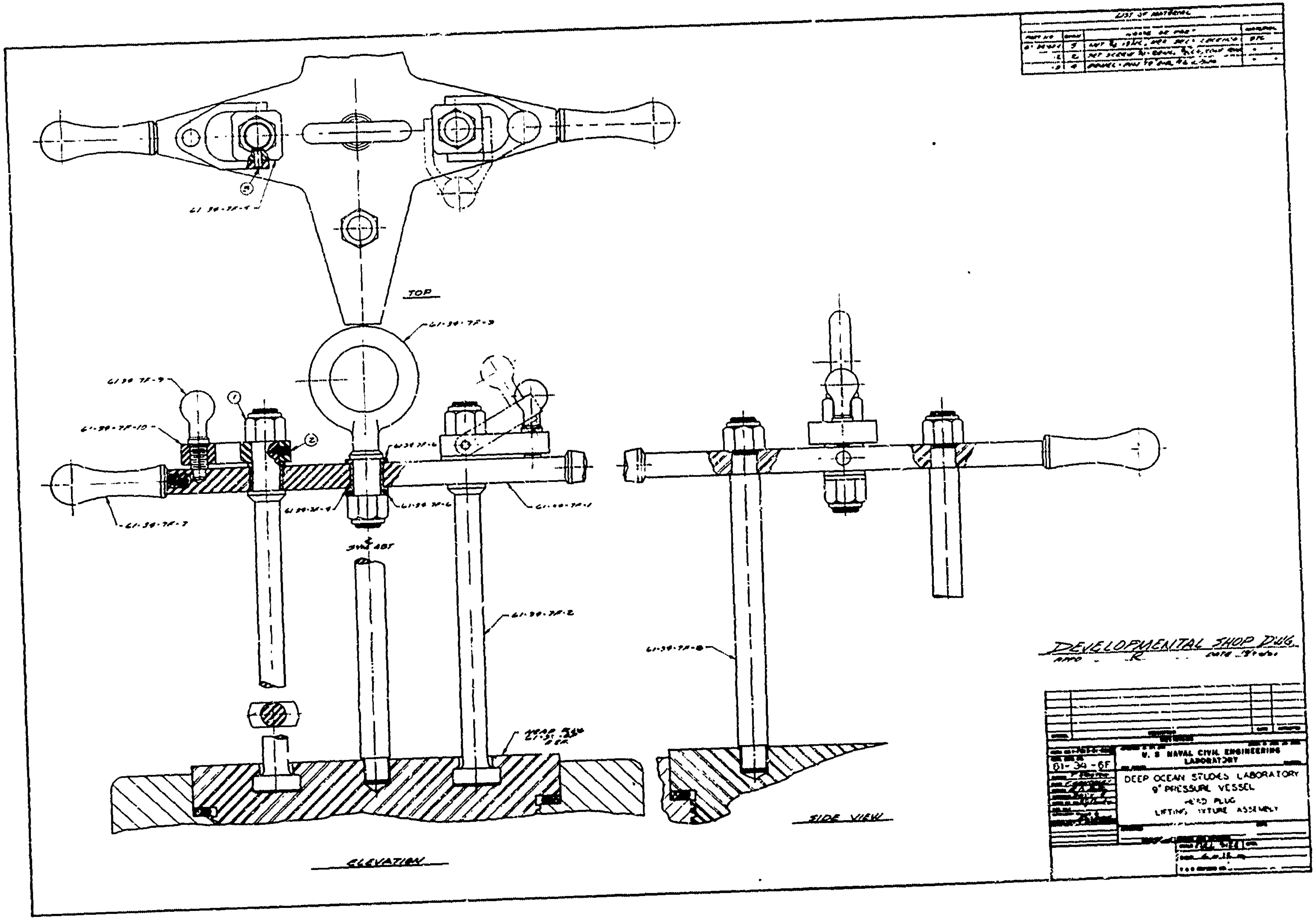


Figure 40. Mk-I head plug turning and lifting device, general assembly.

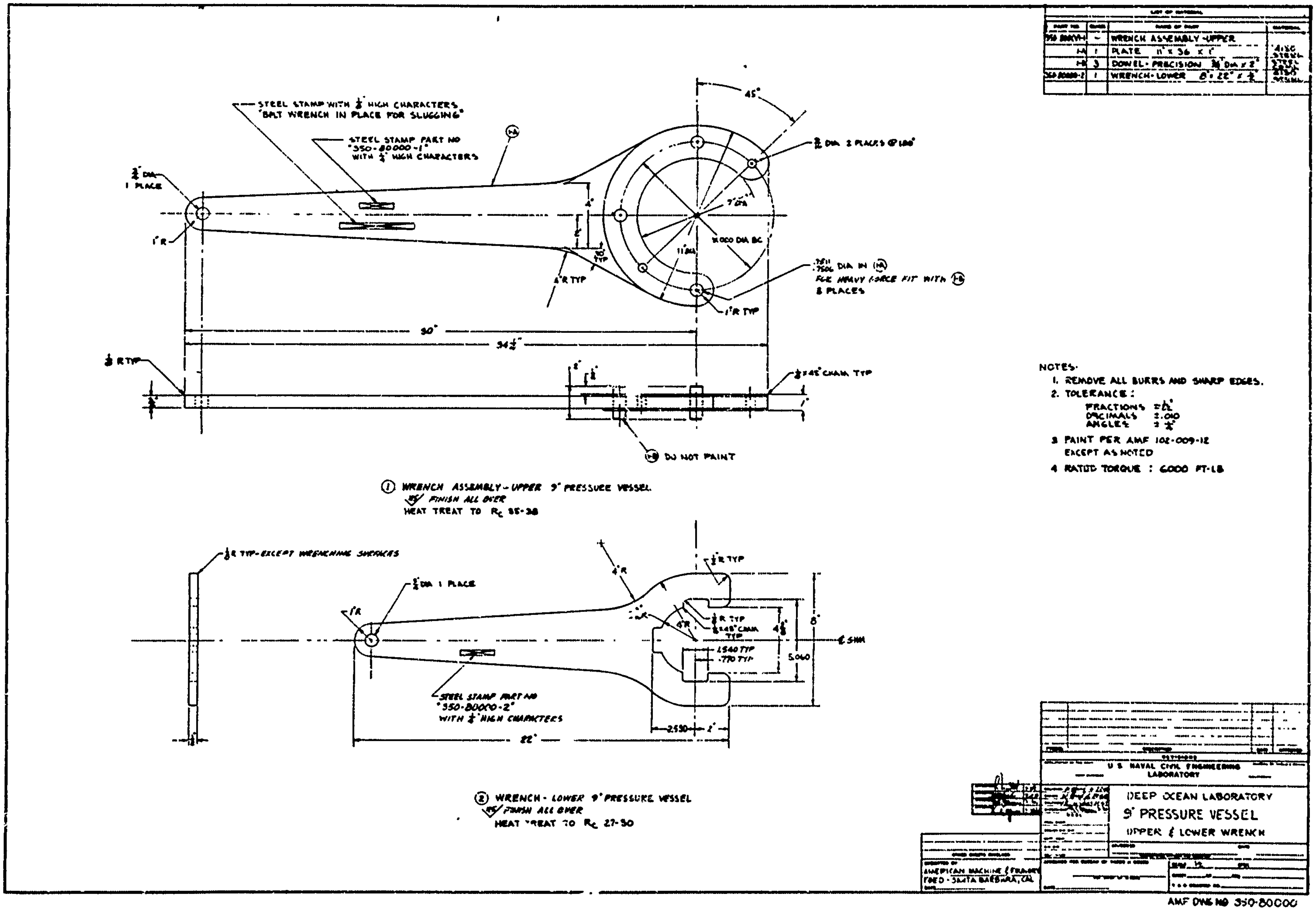


Figure 42. Mk-II locking ring wrenches.

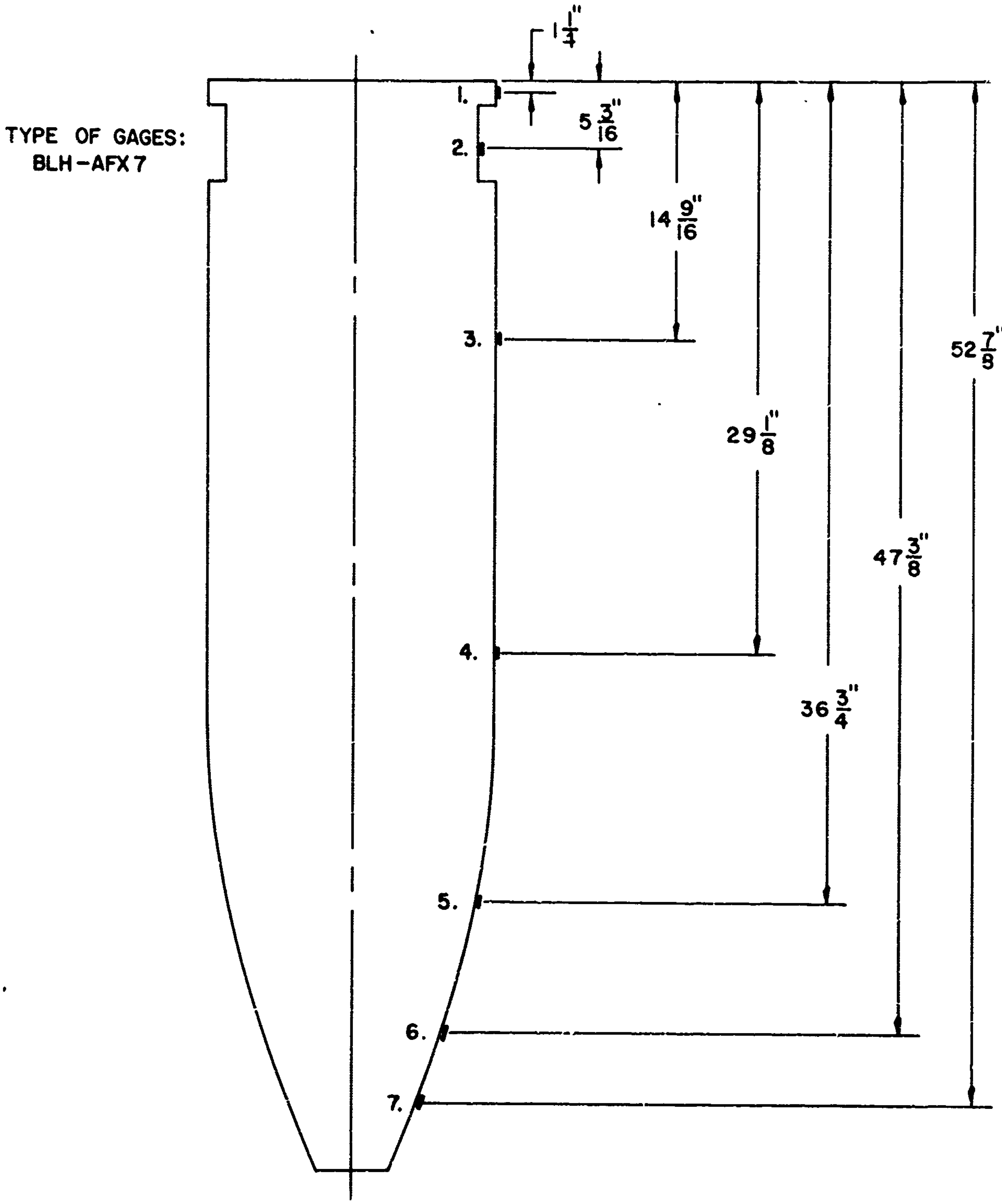


Figure 43. Location of 90° SR-4 strain gage rosettes on Mk-I pressure vessel during proof testing.

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13. ABSTRACT

Pressure vessels for use with fresh water and sea water at pressures up to 20,000 psi have been fabricated from modified 16-inch High Capacity Naval Projectiles. Details for modification of projectiles and the fabrication of supporting equipment are presented. Proof testing procedure and data are described and discussed.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Pressure vessels						
design						
fabrication						
high pressure						
windows						
view ports						
electrical entry						
internal pressure						
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